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Engineering quantum dot-based nanosensors for practical detection of pesticide residues in food and water systems

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ABSTRACT

Pesticide contamination in food and water systems poses significant risks to human health and environmental sustainability, necessitating the development of rapid, sensitive, and on-site detection technologies. This review explores recent advances in quantum dot (QD)-based nanosensors for ultra-sensitive pesticide detection. Owing to their unique optical properties, high surface-to-volume ratio, and tunable fluorescence, QDs enable detection at trace levels ranging from femtomolar to nanomolar concentrations, outperforming many conventional analytical techniques. Various sensing strategies, including fluorescence, electrochemical, photoelectrochemical, and Förster resonance energy transfer (FRET)-based mechanisms, are discussed alongside biorecognition elements such as aptamers, enzymes, and antibodies. Additionally, hybrid systems integrating QDs with metal–organic frameworks, polymers, and nanocomposites demonstrate enhanced sensitivity and selectivity. Despite challenges related to toxicity and matrix interference, QD-based nanosensors offer promising solutions for real-time monitoring, food safety assurance, and environmental protection.

Abbreviation list

Abbreviation	Definition
QD	Quantum dot
QDs	Quantum dots
CQDs	Carbon quantum dots
GQDs	Graphene quantum dots
PEC	Photoelectrochemical
FRET	Förster resonance energy transfer
IFE	Inner filter effect
OPs	Organophosphate pesticides
AChE	Acetylcholinesterase
PET	Photoinduced electron transfer
MIPs	Molecularly imprinted polymers
LOD	Limit of detection
LOQ	Limit of quantification
MRL	Maximum residue limit
QY	Quantum yield
EIS	Electrochemical impedance spectroscopy
DPV	Differential pulse voltammetry
CV	Cyclic voltammetry
WHO	World Health Organization
EPA	Environmental Protection Agency
EFSA	European Food Safety Authority

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1. Introduction

Pesticide contamination has become a major concern worldwide with regard to food security, water, and the sustainability of the ecosystem. The extensive application of pesticides in contemporary farming driven by the need to increase crop productivity and prevent pest diseases has resulted in the storage of toxic substances in food products and environmental matrices. It has been estimated that a considerable part of the pesticides used does not reach its target but is dispersed into soil, water bodies, and the atmosphere, leading to the continual pollution of agricultural ecosystems. These residues may also enter the human food chain through fruits, vegetables, and drinking water, thereby posing potential health risks to populations. Pesticide exposure has far-reaching effects on health. Many pesticides, especially organophosphorus and organochlorine compounds, are acutely toxic and can cause long-term adverse effects, including neurotoxicity, endocrine disruption, carcinogenicity, and reproductive disorders. For example, some pesticide residues are linked to estrogenic and anti-estrogenic effects and have been associated with diseases, including breast cancer. In addition, persistent exposure to low levels of pesticides can lead to bioaccumulation in the human body and cause delayed yet serious health effects (Cordeiro et al., 2023; Issa et al., 2023). These risks highlight the importance of effective monitoring and detection strategies. Environmentally, pesticides often exhibit high persistence and mobility, which enables them to contaminate surface water, groundwater, and soil systems. The main routes by which pesticides enter water bodies include agricultural runoff and leaching processes, which contribute to long-term ecological destruction and interfere with the lives of aquatic organisms. Their resistance to degradation, together with their persistence, complicates remediation efforts and further necessitates continuous monitoring to ensure environmental safety. Pesticides have been widely detected using conventional analytical methods, including gas chromatography–mass spectrometry (GC–MS), liquid chromatography–mass spectrometry (LC–MS), and high-performance liquid chromatography (HPLC), owing to their high accuracy and reliability. However, these techniques have several limitations: they are expensive to operate, require complex sample preparation, are time-consuming, and depend on skilled personnel and laboratory facilities (Pundir and Chauhan, 2012). Such constraints make them unsuitable for rapid and on-site monitoring, particularly in resource-limited settings. To address these challenges, growing interest has been directed toward the development of fast, portable, and highly sensitive detection systems. Nanosensors, namely nanotechnology-based sensors, have emerged as promising options due to their distinctive physicochemical features, including a high surface-to-volume ratio, high reactivity, and tunable optical and electronic properties. These sensors enable detection of contaminants in real time at reduced cost, while providing enhanced sensitivity and selectivity (Willner and Vikesland, 2018). In particular, sensing platforms based on nanomaterials have demonstrated substantial potential for detecting pesticides, heavy metals, and other pollutants in environmental matrices. Quantum dots (QDs), as one class of nanomaterials, have attracted considerable attention as modern sensing elements due to their superior optical performance, including size-controlled fluorescence emission, high photostability, and a broad absorption spectrum. In fluorescence-based sensors, quantum dots can act as efficient signal transducers because of these properties. Moreover, QD-based nanosensors can be functionalized with biomolecules, including aptamers, enzymes, or molecularly imprinted polymers, to target specific analytes. Recent advances indicate that quantum dot-based nanosensors are capable of detecting pesticide residues at extremely low concentrations. For example, cadmium telluride (CdTe) quantum dots incorporated into electrochemiluminescent aptasensors can achieve detection limits of 0.42 fg/mL for diazinon in food samples, characteristic of ultra-sensitive operation (Li et al., 2025). Similarly, fluorescence-based nanosensors using carbon quantum dots have demonstrated high selectivity, rapid response, and low detection thresholds in real food and water samples. Despite the fact that very low detection limits indicate the potential of the QD-based sensor technology, sensitivity alone is not enough for practical pesticide monitoring. In food safety practice, the performance of the sensor should be assessed through the ability to determine pesticide residues in amounts which are compatible with internationally approved maximum residue limits (MRLs), selectively recognize substances with similar structure, tolerate to complex matrixes of samples, and correlate properly with results obtained by recognised chromatographic techniques such as HPLC, LC-MS/MS, and GC-MS/MS. Accordingly, this review evaluates sensor performance beyond sensitivity alone by considering regulatory compliance and practical applicability (Li et al., 2026; Sassolas et al., 2012). Overall, these developments suggest that quantum dot-based nanosensors can overcome limitations associated with conventional analytical methods. From the literature review carried out in this review, a conceptual framework is proposed that connects the use of Quantum dots (QDs) material, surface engineering, recognition strategies, sensing mechanisms, analytical performance and its application. This framework outlines the key engineering requirements to enable QD-based pesticide nanosensors to be moved from laboratory scale research to routine use in food safety and environmental monitoring, and provides a list of the major knowledge gaps that need to be filled. The analytical performance of Quantum dot-based nanosensors should be evaluated not only by their limits of detection but also by their ability to satisfy internationally accepted maximum residue limits (MRLs) established for food and water safety. Therefore, the relevant regulatory requirements are summarized below to provide an appropriate benchmark for assessing practical sensor applicability.

Quantum dots (QDs) possess several physicochemical and photophysical characteristics that make them particularly attractive as signal-transduction materials in nanosensing. Their high fluorescence quantum yields, excellent photostability, long fluorescence lifetimes, broad absorption spectra, and narrow, size-tunable emission bands enable intense and stable optical signals, simultaneous excitation of multiple QDs, and reduced spectral overlap compared with conventional organic fluorophores (Hu et al., 2019; Zhou et al., 2015). In addition, their high surface-to-volume ratio and versatile surface chemistry facilitate functionalization with selective recognition elements, while their tunable electronic properties support efficient charge and energy transfer. QDs are particularly effective donors in Förster resonance energy transfer (FRET) architectures, enabling sensitive signal amplification and multiplexed detection (Hu et al., 2019; Yuan et al., 2025; Zhou et al., 2015). Recent QD-integrated programmable nucleic-acid nanoarchitectures have further demonstrated that spatial organization, confined reactions, and cascade amplification can improve reaction kinetics, sensitivity, selectivity, and multiplexing capability (Yuan et al., 2025a; Yuan et al., 2025b). Collectively, these characteristics provide a strong basis for developing sensitive, selective, and potentially multiplexed QD-based nanosensors for pesticide monitoring in food and water systems. A pesticide-residue monitoring system in food and water systems needs an analytical approach that is both sensitive and selective, and can be field-deployed, simple to operate, and be rapidly analyzed. Although conventional chromatographic techniques can be very precise and reliable, they are not always the most convenient and straightforward methods and require more advanced instrumentation, skilled personnel, and laboratory facilities, as well as more complex sample preparation procedures, in general (Ortiz-Martínez et al., 2024). In addition to the tunable optical/electronic properties, the high surface-to-volume ratio, and the versatile surface chemistry of QD-based nanosensors make them useful for efficient signal generation and for integration with selective recognition elements, which is useful for rapid screening (Zou et al., 2024). Such properties make it possible for the QD to serve in fluorescence, electrochemical, photoelectrochemical, and Förster resonance energy transfer (FRET)-based platforms, in portable devices, in devices that are attached to a smartphone, and in microfluidic devices. As such, the use of QD-based nanosensors to screen pesticide residues in food and

water, especially for decentralized use where quick decision-making is essential, is particularly attractive. However, they are not only limited to having low detection limits, but also need to be selective, tolerant of matrices, stable, reproducible, safe, validated and approved by regulators. Thus, QD-based nanosensors are not intended to replace existing chromatographic reference methods, but rather to be used as complementary screening and monitoring tools (Ortiz-Martínez et al., 2024; Zou et al., 2024). Recently, the advances in the field of quantum dot (QD)-based sensor technologies have widened the scope of nanosensors. Great achievements have been made in engineering the hybrid nanocomposites, functionalizing their surfaces, using DNA aptamers and molecularly imprinted polymers for the detection of pesticides, as well as in multi-target sensing, using smartphones for detection, and employing artificial intelligence in signal processing and creating microfluidic systems for food and water testing. However, it is worth noting that review articles available until now usually deal with a certain type of QDs, a particular sensing principle, or a certain application area without any attempts to combine the basic engineering principles of sensor operation and practical usage. Also, the important topics like structure-activity relationships, matrix effects, reproducibility, commercialization, safety for environment, and regulatory approval are treated separately without trying to conduct integrated analysis. A comprehensive assessment is therefore needed to integrate material design, sensing mechanisms, analytical performance, and translational requirements for the rational development of emerging nanosensors. In order to fulfil this necessity, this paper approaches the issue from the perspective of engineering by systematically linking QD composition, surface processing, composite material development, sensing methodologies, and device design with analytic efficiency and practical application. The newness, scope, and special contribution of the current paper as compared to the previous publications are discussed in the following section.

1.1. Novelty and scope of the present review

While several recent reviews have summarized the use of quantum dots (QDs) in pesticide sensing, most have focused on a specific material system, such as carbon quantum dots, a single sensing mechanism, such as fluorescence or electrochemical detection, or a particular application area, such as food or environmental safety. Consequently, the existing literature remains largely descriptive, with limited critical comparison of the engineering approaches that govern sensor performance and practical applicability. The present review differs from other published reviews in that it employs a comparative engineering-oriented approach, not just a list of published studies. Rather than evaluating QD-based sensing platforms individually, this review systematically examines how QD composition, optical and electronic properties, surface chemistry, hybrid nanocomposite engineering, and biorecognition elements jointly determine analytical performance. The merits, limitations, and practical applicability of fluorescence-based sensing mechanisms, including FRET, electrochemical sensing, photoelectrochemical sensing, and portable sensing platforms are compared with respect to selectivity, matrix tolerance, reproducibility, response time, and field applicability. In addition to its critical assessment of the materials/sensor relationships for various pesticide classes and sample matrices from fruits and vegetables to drinking water, wastewater, and other environmental samples, this work is unique in this content. Rather than focusing solely on detection limits, this review compares analytical performance, recognition strategies, and engineering approaches across QD-based sensing platforms. Particular emphasis is placed on the factors governing sensitivity, selectivity, operational stability, and translation from laboratory prototypes to practical monitoring systems. Key challenges—including matrix interference, long-term stability, reproducibility, standardization, scale-up, regulatory acceptance, and the environmental safety of heavy-metal-based QDs—are critically evaluated together with emerging mitigation strategies. Furthermore, various recent developments are presented in the fields of multiplex detection, sensing with a cell phone, microfluidic devices, data analysis with artificial intelligence, and field-deployable nanosensor platforms, with an eye to their readiness for practical use. A comparison of representative recent review articles with the present review is provided in Supplementary **Table S1** to clarify differences in scope, remaining knowledge gaps, and the specific contributions of the present work. To minimize redundancy in the main manuscript, the comparison with previous reviews is provided in Supplementary Table S1, whereas the main-text comparative tables address three distinct analytical levels: QD material characteristics and safety (Table 4), analytical-method performance (Table 12), and matrix-specific practical implementation (Table 14). This broad, application-oriented review integrates materials engineering, sensing mechanisms, analytical performance, practical implementation, and translational perspectives within a single critical framework. It also provides engineering-oriented design considerations for next-generation QD-based pesticide nanosensors, with particular emphasis on the relationship between material properties, sensor architecture, analytical performance, and practical applicability.

The review's primary aim is not simply to recapitulate recent advances in quantum dot (QD)-based pesticide sensing but to set forth an engineering-related framework that elucidates how material design, surface engineering, sensing mechanisms, and device architecture together dictate analytical efficiency and practical feasibility of application. Although recent reviews have addressed individual QD classes or specific sensing methods, the present review provides a broader comparative analysis of engineering strategies in terms of sensitivity, selectivity, stability, reproducibility, and operating conditions. Particular attention is given to structure–activity relationships, hybrid nanocomposite engineering, surface modification, recognition strategies, and the translation of laboratory-scale QD nanosensors into portable analytical devices for food and water monitoring. This approach enables a more integrated assessment of the factors that govern both analytical performance and practical implementation. The review moves from discussion of the general properties of QDs to engineering principles of design, methods of sensing, and questions of comparative performance evaluation of systems and technologies based on QDs. Fig. 1 presents the engineering-oriented conceptual framework proposed in this review for the rational development and translation of QD-based pesticide nanosensors.

2. Search methodology

2.1. Review design, scope, information sources, and search period

This review was conducted as a structured narrative review supported by a PRISMA-style literature identification and screening framework to improve the transparency and consistency of study selection. The review focused on quantum dot (QD)-based nanosensors for pesticide detection, with particular attention to QD composition, surface modification, recognition strategies, signal-transduction mechanisms, analytical performance, and applications in food and water analysis. Because the available studies differed considerably in QD materials, sensing formats, target pesticides, sample matrices, and analytical performance measures, quantitative meta-analysis was not considered appropriate. The primary literature search covered publications from 2015 to 2025, while selected earlier studies were consulted only when necessary to provide historical or conceptual context. The formal search was conducted in Scopus, Embase, Web of Science, and PubMed. In total, 9,994 records were identified, including 2,785 from Scopus, 2,100 from Embase, 2,471 from Web of Science, and 2,638 from PubMed.

2.2. Search strategy

The search strategy was developed around the main concepts of the review and was adapted to the search functions and indexing systems of

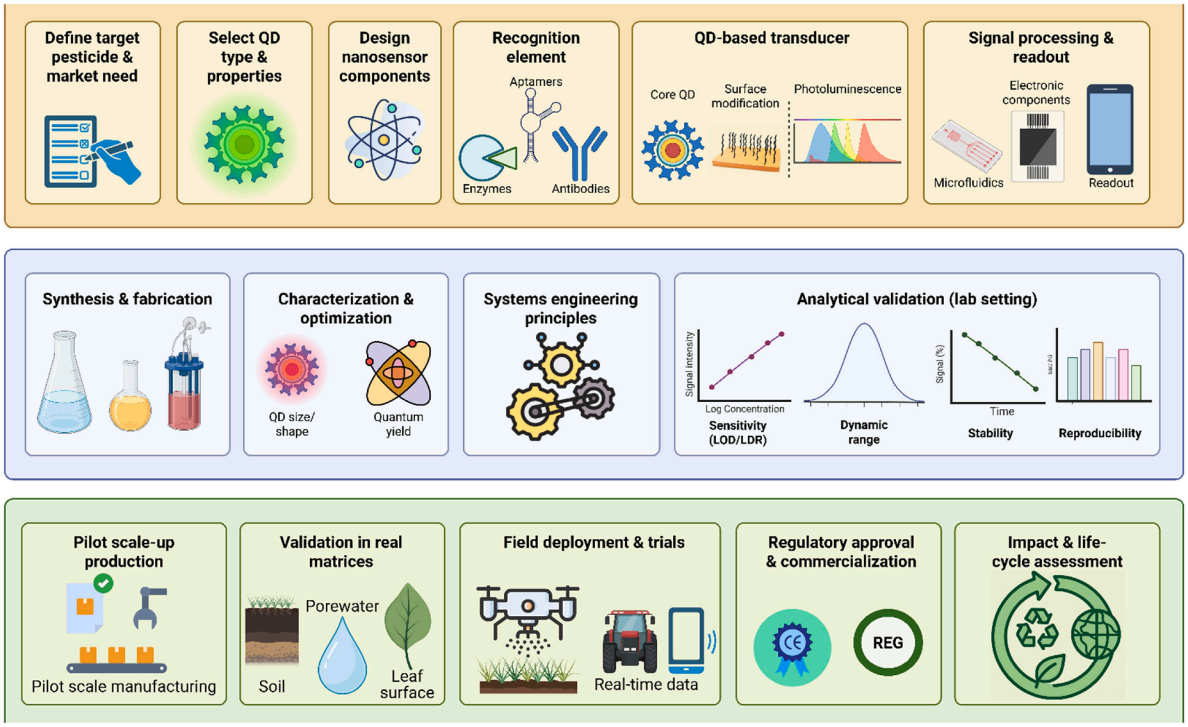


Fig. 1. Engineering-oriented conceptual framework adopted in this review for the rational development and translation of QD-based pesticide nanosensors.

each database. Representative search terms included quantum dots, quantum dot-based nanosensors, carbon quantum dots, graphene quantum dots, semiconductor quantum dots, pesticide detection, pesticide residues, food analysis, water analysis, fluorescence sensor, FRET, electrochemical sensor, electrochemiluminescence, photoelectrochemical sensor, aptasensor, and acetylcholinesterase biosensor. Related terms were combined using the Boolean operator OR, while the principal concept groups were linked using AND. All retrieved records were consolidated before screening. Of the 9,994 initially identified records, 7,221 were removed before title and abstract screening, including 4,916 duplicates, 15 book chapters, 670 records excluded according to the language criterion, 1,078 records outside the predefined publication period, 30 retracted papers, and 512 records removed for other predefined reasons. Following this initial filtering, 2,773 records remained for screening.

2.3. Eligibility criteria and study selection

Studies were considered eligible when they were peer-reviewed research articles investigating pesticide detection using a nanosensor or biosensor platform in which QDs played a direct role in sensing, signal generation, energy or charge transfer, or signal amplification. Eligible studies were also required to provide sufficient information on sensing mechanisms, QD composition, analytical performance, or validation in relevant food or water samples. During title and abstract screening, 1,815 records were excluded because they were outside the review scope (n = 198), did not involve a QD-based sensing platform (n = 371), did not investigate pesticide detection (n = 567), provided insufficient analytical-performance data (n = 443), or represented an ineligible publication type (n = 236). Of the 958 reports sought for retrieval, 351 were not retrieved, leaving 607 reports for full-text assessment. A further 335 reports were excluded at this stage, and 272 studies were ultimately included in the final qualitative and comparative synthesis (Fig. 2).

3. Pesticides: classification, environmental fate, toxicity, and analytical requirements

3.1. Pesticide classes, contamination pathways, and toxicological relevance

Pesticides can be grouped according to their chemical composition and mechanisms of action. The most widely used classes include organophosphates, carbamates, pyrethroids, and neonicotinoids. The application of these classes in contemporary agriculture supports crop production; however, it has also contributed to contamination of food and water systems with compounds that are often persistent and toxic. Organophosphates (OPs) are among the most prevalent pesticides due to their high effectiveness against a broad range of pests. Neurotoxic compounds in this category—malathion, diazinon, chlorpyrifos, and phorate—exert their effects by inhibiting acetylcholinesterase (AChE), leading to acetylcholine accumulation and consequent neurotoxicity in both target and non-target organisms. Research indicates that, even at low exposure levels, organophosphates can be lethal and may adversely affect human neurophysiological functions, with long-term health-related consequences. Carbamates are another important pesticide class. They inhibit acetylcholinesterase in a reversible manner. One of the most commonly used carbamates is carbaryl, whose residues have been detected in agricultural products, including vegetables and fruits. The lowest reported detection limits for nanomaterial-based electrochemical sensors contribute to the widespread occurrence of carbamate contamination and the development of sensitive detection technologies (Banglani et al., 2026). Although carbamates are generally less persistent than organophosphates, they are frequently released to the environment and are therefore detected in environmental compartments, particularly surface waters. Synthetic analogs of natural pyrethrins are pyrethroids, which are widely used due to their relatively low mammalian toxicity compared with other pesticide classes. However, pyrethroids are highly toxic to aquatic organisms and may persist in the environment under certain conditions. Pyrethroids, such as permethrin and deltamethrin, have been frequently observed in environmental surveillance studies, including investigations of insecticide-resistant

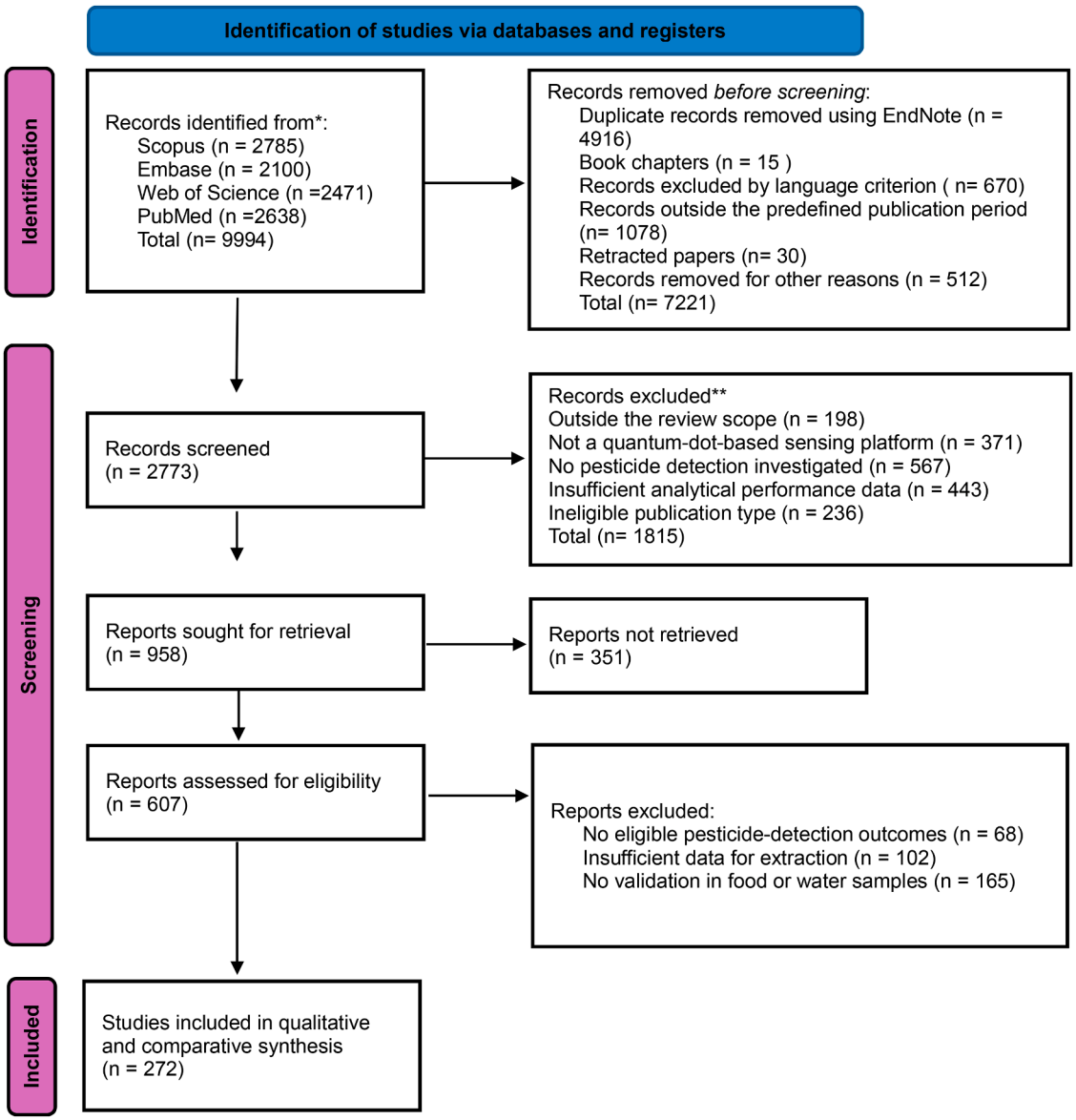


Fig. 2. PRISMA 2020-style flow diagram illustrating the identification, screening, eligibility assessment, and final inclusion of studies on quantum dot (QD)-based nanosensors for pesticide detection.

mosquitoes. Due to their hydrophobic nature, pyrethroids accumulate in sediments and occur in aquatic organisms, which promotes bio-accumulation and trophic transfer through food chains. Neonicotinoids are systemic insecticides that target nicotinic acetylcholine receptors in insects. Common examples include imidacloprid and acetamiprid. These substances are relatively soluble in water and therefore may leach into groundwater and surface water bodies. Imidacloprid is one of the most frequently detected neonicotinoids in food and environmental sources and has been associated with respiratory toxicity, liver toxicity, and possible carcinogenicity (Boonyong and Powthong, 2026). Table 1 Pesticide classes, representative matrices, and associated toxicological effects.

Pesticides contaminate both food and water systems through multiple pathways, which are driven primarily by agricultural activities. Agricultural runoff is among the most significant routes for water contamination (Ma et al., 2026). Moreover, pesticides that are very soluble in water like imidacloprid will diffuse quickly from soil to water, and they are often found in water sources such as ponds and in crops (Li et al., 2026). The soil–plant–water transfer system allows for the movement of pesticides from the soil into crops, and eventually into our food supply. Once the pesticides are applied, they can either stay bound to the soil or dissolve in the soil water to be absorbed by the roots (Cui et al., 2026; Zhang et al., 2023). This shows that if soil becomes contaminated with pesticides, the resulting food may also be unsafe. In addition to contaminants entering the food system pre-harvest, the way the food is processed and handled after it is harvested can add or reduce the concentration of pesticide residues that may have come from either the soil or the growing process. During food handling (e.g., washing, boiling, refrigerating, and cooking food), the amount of residue will change due to the handling techniques; the processing factor can vary from 0.01 to 1.69 depending on each type/amount of processing method. The majority of the time, washing and boiling food will reduce the amount of pesticide residue. However, sometimes methods such as very long stir-frying will start to decrease the level of residue, but at a certain point will start to accumulate more pesticide residue due to the lack of water and increased concentration (Cui et al., 2026). Fig. 3 illustrates pesticide transfer through agricultural runoff, soil–plant–water pathways, and post-harvest contamination.

Pesticide residues are commonly detected in food products and in water systems, raising major concerns regarding food safety and

Table 1
Representative pesticides detected in food and environmental matrices, their chemical classes, and major toxicological concerns relevant to pesticide exposure and monitoring.

Pesticide	Chemical class	Representative matrix	Principal toxicological concern	Suggested evidence	Ref.
Diazinon	Organophosphate	Fruits, vegetables, water	AChE inhibition; neurotoxicity; carcinogenic hazard classification	IARC/WHO	(Li et al., 2025)
Malathion	Organophosphate	Food and agricultural matrices	AChE inhibition; neurotoxicity; carcinogenic hazard classification	IARC/WHO	(Wu et al., 2025)
Phorate	Organophosphate	Vegetables, soil, water	Cholinesterase inhibition; acute neurotoxicity	Toxicological literature	(Zhang et al., 2026)
Chlorpyrifos	Organophosphate	Soil, water, food	Cholinesterase inhibition; neurodevelopmental concerns	EPA	(Jain et al., 2026)
Carbaryl	Carbamate	Tomato, potato, vegetables	Reversible AChE inhibition; neurotoxicity	Toxicological literature	(Banglani et al., 2026)
Thiodicarb	Carbamate	Vegetables	Cholinesterase inhibition; acute toxicity	Toxicological literature	(Sivaraj et al., 2026)
Fenpyroximate	Phenoxy-pyrazole/ acaricide	Vegetables	Mitochondrial respiratory-chain disruption; oxidative effects	Toxicological literature	(Sivaraj et al., 2026)
Permethrin	Pyrethroid	Food/environmental matrices	Voltage-gated sodium-channel disruption; neurotoxicity	Toxicological literature	(Obuobi et al., 2026)
Deltamethrin	Pyrethroid	Food/environmental matrices	Sodium-channel modulation; neurotoxicity	Toxicological literature	(Obuobi et al., 2026)
Imidacloprid	Neonicotinoid	Water, cabbage, apple	Nicotinic acetylcholine receptor activity; neurotoxicity; ecological toxicity	Toxicological/ ecotoxicological literature	(Boonyong and Powthong, 2026; Li et al., 2026)
Thiamethoxam	Neonicotinoid	Food/environmental matrices	Nicotinic receptor-mediated toxicity; ecological toxicity	Ecotoxicological literature	(Liu et al., 2025)
Glyphosate	Herbicide	Vegetables, water, soil	Genotoxicity; carcinogenic hazard classification by IARC	IARC	(Hou et al., 2026)
Fipronil	Phenylpyrazole	Water, fish, food	GABA-gated chloride-channel disruption; neurotoxicity; ecological toxicity	Toxicological literature	(Ma et al., 2026)
Paraquat	Bipyridyl herbicide	Soil, water, fruits	Acute systemic toxicity; oxidative stress; pulmonary toxicity	Toxicological literature	(Yang et al., 2026)
Pyrimethanil	Anilinopyrimidine fungicide	Pepper juice, vegetables	Toxicological effects associated with exposure; residue concern	Toxicological literature	(Jain et al., 2026)
Atrazine	Triazine herbicide	Water, vegetables	Endocrine-related effects; reproductive/ developmental concerns	Regulatory/toxicological literature	(Banglani et al., 2026)
Fipronil sulfone	Fipronil transformation product	Aquatic/ environmental systems	Persistence and ecological toxicity; receptor-mediated neurotoxicity	Environmental toxicology	(Sivaraj et al., 2026)
Prometryn	Triazine herbicide	Water	Aquatic/ecological toxicity	Ecotoxicological literature	
Difenoconazole	Triazole fungicide	Tomatoes, fruits	Hepatic and developmental/reproductive toxicity concerns	Toxicological literature	(Li et al., 2026)
Carbendazim	Benzimidazole fungicide	Food/vegetables	Reproductive/developmental toxicity; endocrine-related effects	Toxicological literature	(Öncer et al., 2026)
Dicamba	Benzoic-acid herbicide	Food/environmental matrices	Systemic toxicity and environmental effects	Regulatory/toxicological literature	(Chen et al., 2026)

environmental sustainability. Residues have been documented in fruits, vegetables, and processed food matrices, including tomatoes, peppers, cabbage, apples, and grains. For instance, surface-enhanced Raman spectroscopy (SERS)-based platforms have successfully identified residues of difenoconazole in tomatoes at concentrations as low as 32 μg/kg, demonstrating the ubiquitous presence of this contaminant in common food items (Luong et al., 2026). Notably, imidacloprid has also been found ubiquitously in food and water environments, with high recovery values in food (93.69–105.23%) and in water (70.38–75.62%) (Li et al., 2026). Moreover, levels of organophosphorus pesticides in fruit juices have been reported to range from 0.25 to 200 μg/L, indicating contamination of processed beverages as well (Mohamed-Benhamu and Martínez-Guitarte, 2026). Exposure risks are further increased by the presence of pesticides in drinking and irrigation water. Monitoring studies of water bodies have reported chronic contamination with pesticides such as fipronil and its transformation products, with detections in estuarine environments at 0.826–6.23 ng/L and in sediments and aquatic organisms (Ma et al., 2026). These findings emphasize the ongoing contribution and persistence of pesticide residues in irrigation and drinking water. Regarding human health, pesticide exposure can result in acute toxicity, chronic disease, and bioaccumulation. Specifically, imidacloprid has been linked to respiratory toxicity, liver toxicity, and possible carcinogenicity through mechanisms involving oxidative stress and inflammatory signaling pathways (Boonyong and Powthong, 2026). Similarly, organophosphate pesticides such as malathion act as acetylcholinesterase inhibitors, resulting in neurotoxicity even at low doses. The occurrence of pesticide residues in food and water systems and their associated human health and ecological impacts are summarized in Fig. 4. Additionally, when pesticide residues undergo transformation to generate metabolites, they have been shown to disrupt metabolic and reproductive pathways in aquatic organisms, suggesting potential ecosystem-wide effects (de Arruda Leite et al., 2026). Pesticide residues in food and water systems must be controlled to ensure public health and safety. Global regulatory bodies, including the World Health Organization (WHO), the United States Environmental Protection Agency (EPA), and the European Food Safety Authority (EFSA), establish maximum residue limits (MRLs) in food and permitted concentration levels in drinking water. These guidelines are based on toxicology risk assessments, including Acceptable Daily Intake (ADI) and Acute Reference Dose (ARfD), to reduce human exposure to hazardous residues. MRLs in food vary according to pesticide identity and commodity type (Chen et al., 2026). Collectively, these results indicate that current analytical methods particularly nanosensor-based systems can detect pesticide traces well below regulatory standards. For water systems, regulatory limits are generally stricter because water is consumed directly by humans and is also subject to ecological considerations. Drinking water standards typically require low maximum concentrations for individual pesticides, often at levels of ng/L or lower. An example is the detection of imidacloprid in the environment at 0.25 μg/L, which is consistent with or close to permissible limits and may be of concern in cases of accumulation (Li et al., 2026)

In addition, pesticide pollution in water sources, such as the presence

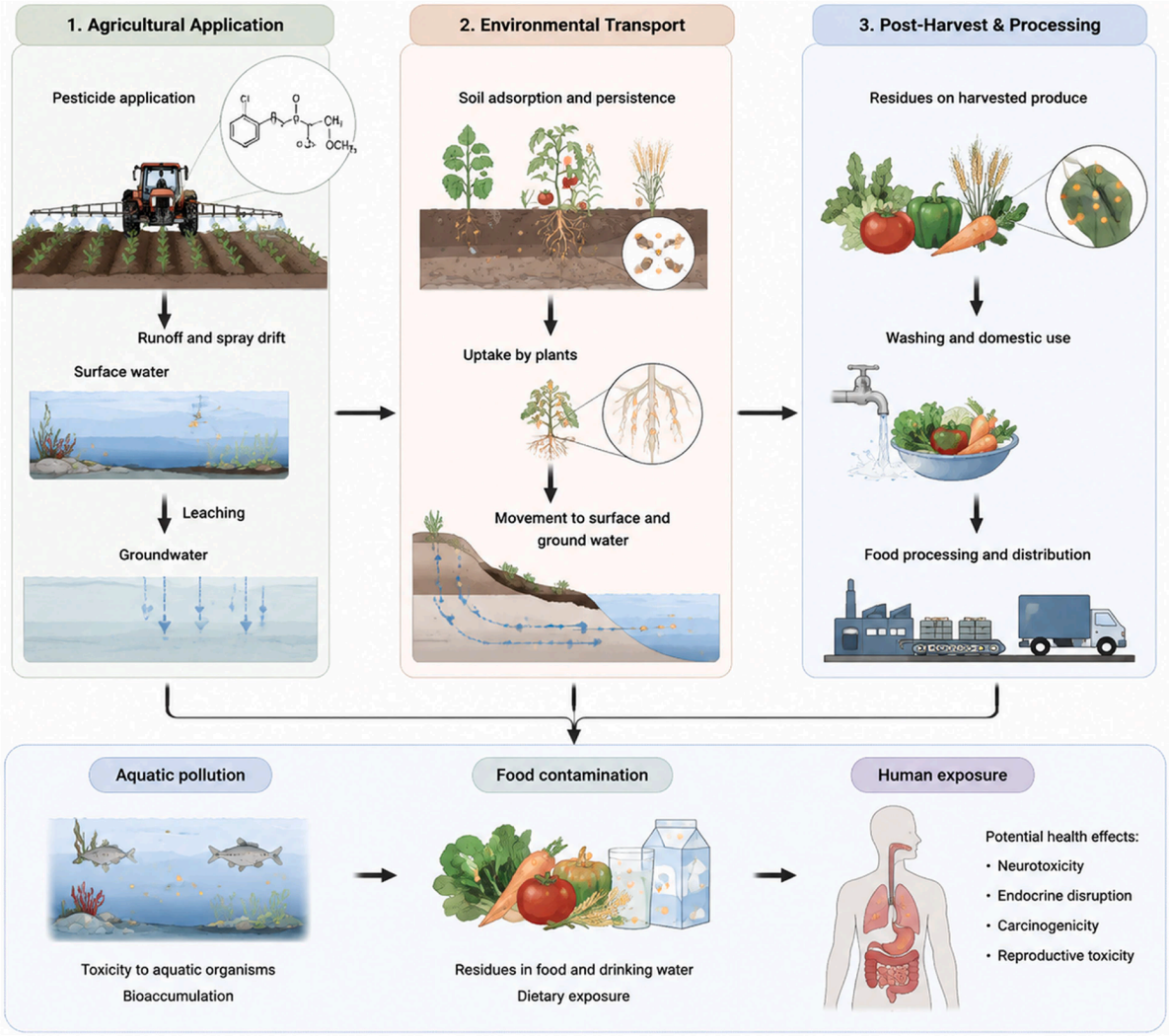


Fig. 3. Schematic overview of pesticide contamination pathways from agricultural application through soil–water transfer, food contamination, and potential human exposure.

of fipronil at 0.826–6.23 ng/L, highlights the need for routine monitoring and regulatory implementation (Ma et al., 2026). Although regulatory frameworks exist, challenges remain because pesticide mixtures, transformation products, and bioaccumulation effects are not always fully addressed by current standards. As a result, identifying state-of-the-art detection technologies and implementing ultra-sensitive, real-time monitoring are increasingly necessary. Nanosensors based on quantum dots are promising tools for detection at concentrations around 0.1 μg/L, which are far below regulatory thresholds and may help align monitoring practices with global food safety standards. Table 2 summarizes selected pesticide limits and associated health concerns across WHO, U.S. EPA, and EU regulatory frameworks.

An important note regarding detection limit units: Detection limits (LODs) are recorded in the same units as used in the original studies (for example, fM, pM, nM, ng/mL, μg/L, and μg/kg) so that no unnecessary complications arise from additional conversion of units. For purposes of comparison, equivalent concentrations are subsequently converted into a common reference unit for reliable conversion of molecular weights and identities of analytes. As a matter of principle, given that the mass- and molar-based LODs cannot be switched directly without obtaining information about molecular weights, both units remain in use.

4. Fundamentals of quantum dots for sensing applications

4.1. Structure and composition

In the applications of quantum dots for the detection of pesticides, it is possible to make general classifications on the basis of the composition and structure of quantum dots. Because of the variations in the physicochemical characteristics of major quantum dot families, their analytical characteristics, environmental safety, stability, and overall applicability also differ. Therefore, an understanding of the properties of different groups of quantum dots is a prerequisite for choosing appropriate sensor materials for use in food and water industry. In this review, the evaluation of quantum dots involves their classifications into: (i) semiconductor quantum dots; (ii) carbon quantum dots; (iii) graphene quantum dots; (iv) silicon quantum dots; (v) perovskite quantum dots; and (vi) hybrid quantum dot nanocomposites. The next sections of this article will give a critical comparison of the above-mentioned material classes from both technical and application perspective (Omari et al., 2026; Quesada-González and Merkoçi, Apr 1 2025). This section establishes the physicochemical principles that govern the engineering of high-performance QD-based sensing platforms discussed in the subsequent sections. Quantum dots (QDs) are nanoscale semiconductor materials whose distinct optical and electronic properties arise from quantum confinement effects. QD structure and composition are critical

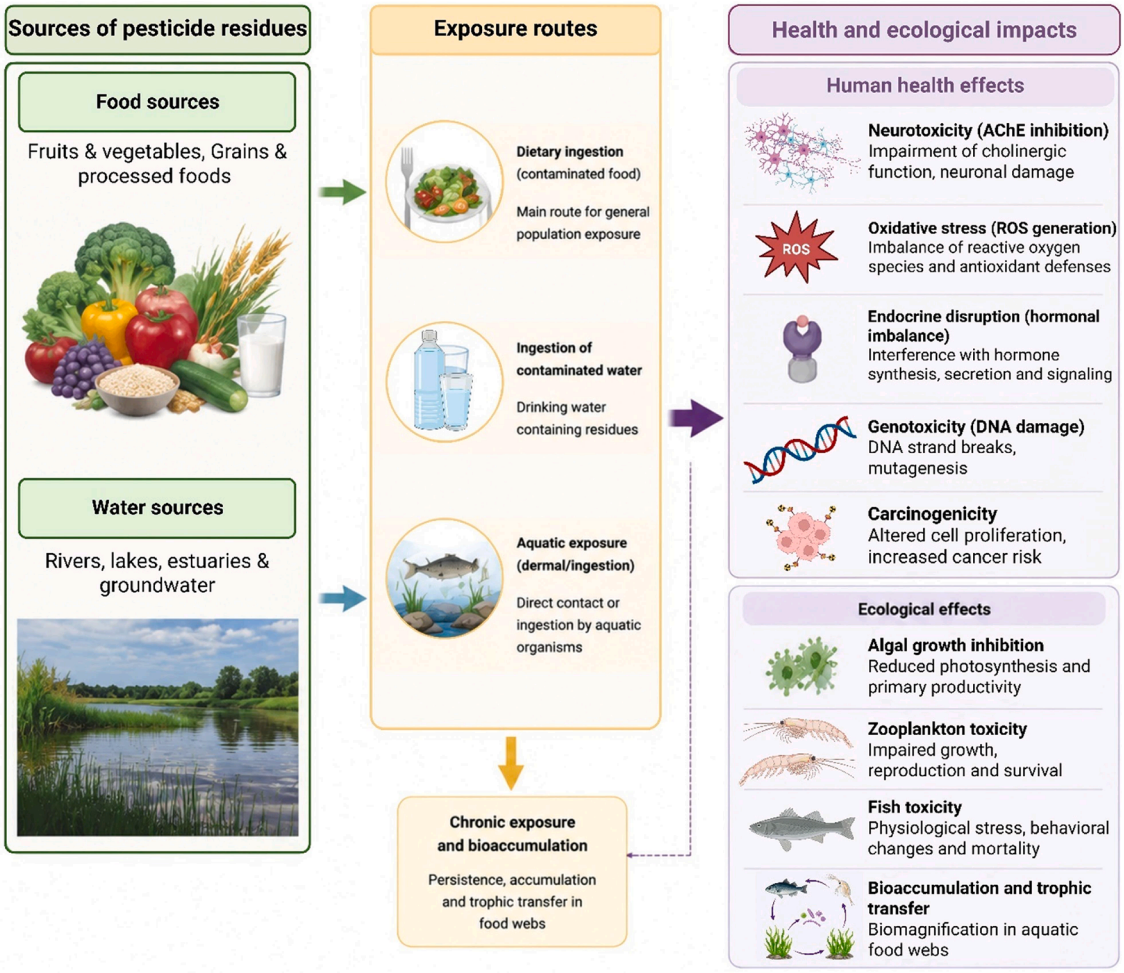


Fig. 4. Pesticide residues in food and water and their potential health and ecological impacts.

for controlling photoluminescence behavior, surface reactivity, and sensing capability. Although QDs are suitable for application as nanosensors in ultra-sensitive pesticide detection, their tunable emission characteristics, high surface-to-volume ratio, and ease of functionalization have made them particularly appropriate for this purpose. The most widely studied QDs are cadmium-based quantum dots (Cd-QDs), including cadmium selenide (CdSe) and cadmium selenide/zinc sulfide (CdSe/ZnS) core–shell structures. These designs offer high quantum yield, narrow emission spectra, and excellent photostability. Core–shell architectures (e.g., CdSe/ZnS) are useful for increasing fluorescence efficiency and chemical stability by mitigating surface defects and reducing non-radiative recombination pathways. For example, ZnSe/CdSe core–shell QDs with particle sizes of approximately 4.6 nm exhibit high selectivity and strong fluorescence in sensing-mode operation, with detection limits in the micromolar range. Nevertheless, concerns regarding cadmium toxicity have driven the development of alternative nanomaterials that are considered less harmful to the environment. Zinc-based QDs, particularly ZnS QDs, have emerged as viable alternatives with favorable optical properties and chemical stability. ZnS is used as either a common shellmaterial or as a free-standing QD because it has a large bandgap and can improve fluorescence efficiency. ZnS QDs can be functionalized and exhibit strong luminescence and selective sensing performance due to fluorescence quenching and host–guest interactions that are relevant for detecting trace analytes in complex matrices (Shah et al., 2026). Another significant class of semiconductor quantum dots that have optical properties with high tunability and narrow emission bands is the perovskite quantum dots (PQDs). They are proposed as good fluorescence-based sensing materials due to their composition-dependent bandgap and high photoluminescence. In particular, the association of perovskite QDs with molecularly imprinted polymers has been proven for the recognition of pesticides. For instance, organophosphorus pesticides (OMPs) were selectively detected by fluorescence using perovskite QDs with molecularly imprinted polymer (MIP) as the recognition layer (Huang et al., 2018). However, the chemical stability, lead ion leaching, environmental safety and long-term stability of operation are special concerns in the use of perovskite QDs for food and environmental sensing. In practice, the use of PQD based pesticide sensors will depend on the successful development of effective coatings or encasings and in-depth studies of the toxicological and environmental impact of such sensors. Carbon quantum dots (CQDs) represent an additional metal-free class of nanomaterials with high water solubility, low toxicity, and facile production from green feedstocks. CQDs exhibit tunable fluorescence emission that depends on particle size, surface functional groups, and heteroatom doping (e.g., N, P, or metal-ion doping). More recent studies indicate that doped CQDs can achieve large quantum yields and improved photostability while providing sensitive fluorescence responses; the detection limits of doped CQDs can be as low as 0.016 μg/mL in environmental samples (Alqahtani et al., 2026). In addition, functionalized CQDs enhance catalytic and sensing capabilities, including reactive oxygen species generation and fluorescence quenching, which is beneficial for detecting contaminants (Hao et al., 2026). Graphene quantum dots (GQDs) are based on quantum confinement of graphene or graphene oxide, which provides electronic conductivity comparable to that of graphene with a high accessible surface area. These features enable efficient charge transfer and generate strong fluorescence signals,

Table 2
Health-based guideline values and regulatory parameters for selected pesticide residues in drinking water and food.

Pesticide	Matrix	WHO Limit	EPA Limit	EFSA Limit	Notes (Toxicity Concern)
Imidacloprid	Drinking water	Not specifically set (guideline use risk-based)	0.4 μg/L (chronic benchmark)	0.1 μg/L (EU drinking water directive default)	Neurotoxicity, liver toxicity
Atrazine	Drinking water	2 μg/L	3 μg/L (MCL)	0.1 μg/L (EU limit)	Endocrine disruption
Glyphosate	Drinking water	900 μg/L	700 μg/L (MCL)	0.1 μg/L (EU limit)	Possible carcinogenicity
Chlorpyrifos	Drinking water	Not established	2 μg/L (reference level)	0.1 μg/L (EU default)	Neurotoxicity, developmental toxicity
Diazinon	Drinking water	0.6 μg/L	1 μg/L (lifetime advisory)	0.1 μg/L	Neurotoxicity
Malathion	Drinking water	900 μg/L	200 μg/L	0.1 μg/L	Neurotoxicity
Carbaryl	Drinking water	7 μg/L	40 μg/L	0.1 μg/L	Neurotoxicity
Paraquat	Drinking water	10 μg/L	3 μg/L	0.1 μg/L	Acute toxicity, oxidative stress
Fipronil	Drinking water	Not established	0.2 μg/L (benchmark)	0.1 μg/L	Bioaccumulation, neurotoxicity
Thiamethoxam	Drinking water	Not established	Not established	0.1 μg/L	Neurotoxicity (pollinators)
Pesticide (general)	Drinking water	—	—	**0.1 μg/L (single pesticide)**	EU precautionary limit
Total pesticides	Drinking water	—	—	**0.5 μg/L (total)**	Combined exposure limit
Organophosphates	Food (MRLs)	Risk-based (ADI/ARfD)	Varies by crop (e.g., 0.01–10 mg/kg)	Strict MRLs (0.01–5 mg/kg)	Neurotoxicity
Carbamates	Food (MRLs)	Risk-based	0.01–10 mg/kg	0.01–5 mg/kg	Neurotoxicity
Pyrethroids	Food (MRLs)	Risk-based	0.01–5 mg/kg	0.01–3 mg/kg	Neurotoxicity
Neonicotinoids	Food (MRLs)	Risk-based	0.01–3 mg/kg	0.01–0.5 mg/kg	Neurotoxicity, ecological risk
Atrazine	Food	Not common (restricted)	0.1–3 mg/kg	Restricted/banned in EU	Endocrine disruption
Glyphosate	Food	ADI-based	Up to 20 mg/kg (crop dependent)	0.1–10 mg/kg	Carcinogenic concern
Chlorpyrifos	Food	Risk-based	0.01–10 mg/kg	Banned (EFSA)	Developmental neurotoxicity
Carbaryl	Food	Risk-based	0.1–10 mg/kg	Restricted	Neurotoxicity

(Authority et al., 2019; Boonyong and Powthong, 2026; Dettori et al., 2022; EPA; WHO, 2017)

thereby increasing sensing performance. Heteroatom-doped and functionalized GQDs can exhibit improved photophysical properties, high quantum yields, and detection limits in the nanomolar range, making them useful for bioreceptor-based sensing as well as environmental monitoring (Kuo et al., 2026).

4.2. Optical and electronic properties

QDs are characterized by a number of extraordinary optical and electrical characteristics, which is why they can be easily used in ultra-sensitive pesticide residue detection in food and water systems. These properties are because of their nanoscales, quantum effects of confinement, and electronically tuneable designs. The size-dependent emission is one of the most crucial ones, the optical properties of QDs can be accurately adjusted according to the size. The smaller QDs have a larger band gap and emit light with shorter wavelength whereas larger QDs emit larger wavelengths. This tunability allows multiplexed results in detecting and colorimetric sensing various analytes. Colloidal QDs are said to have size-dependent and size-tunable optical behaviour that are needed in developing versatile sensing platforms (Bertucci et al., 2025). Additionally, the photoluminescence properties are size-dependent and have been proved using the advanced spectroscopic characterization (Stiegler et al., 2026). The other essential property is that the QDs have a high quantum yield (QY) meaning their ability to transform the absorbed light into produced fluorescence. High QY has the benefit of amplifying the signal and increasing the sensitivity of detection. As an illustration, CQDs with a quantum yield of around 17% exhibit high levels of fluorescence and high levels of sensing ability (Pei et al., 2025). Moreover, more sophisticated quantum dot systems can reach near-unity quantum yield that is much better at increasing the sensitivity of analysis (Stiegler et al., 2026). QDs also have a greater molar extinction coefficient compared to traditional dyes, as well as a longer fluorescence lifetime (Muralimanohar and Kumar, 2025). The other important advantage of QDs is photostability. In comparison to the other works, QDs are stable to fluorescence due to prolonged irradiation, unlike the traditional fluorophores which experience rapid bleaching. The use of silicon quantum dots, as an example, has a stable emission with UV irradiation and a broad pH, which is applicable in detecting real samples (Pei et al., 2025). Nitrogen-doped carbon dots can also maintain long-term fluorescence performance, supporting their suitability for long-term sensing applications (Lotey et al., 2025). Beyond these fundamental features, QDs provide broad absorption and sharp emission spectra, enabling efficient excitation of multiple probes simultaneously with minimal spectral overlap. Their high surface-to-volume ratio facilitates functionalization with biomolecules, thereby improving selectivity toward pesticide targets. Moreover, QDs can support photoinduced electron transfer (PET) and fluorescence resonance energy transfer (FRET), both of which are critical for designing sensitive detection systems. For example, QD-based ratiometric fluorescence platforms have demonstrated detection limits as low as the nanomolar range, with high specificity and short response times (Qin et al., 2025). Overall, size-tunable emission combined with high quantum yield is central to the performance of QD-based sensing platforms.

4.3. Types of QDs for environmental and food analysis

In relation to environmental and food analysis, quantum dots can be categorized based on their chemical composition and structural features into various main categories, which include heavy-metal semiconductor quantum dots, fairly harmless semiconductor quantum dots, carbon quantum dots, graphene quantum dots, silicon quantum dots, and perovskite quantum dots. Heavy-metal semiconductor quantum dots such as CdSe and CdTe have been known to show good optical performance, high quantum yield, and very narrow emission band. On the

contrary, carbon and other new families of quantum dots have benefits of having less toxicity, compatibility with environment, etc. The classification mentioned in this section is relevant only for materials that are quantum dots and form the quantum dot part of sensing systems. At the same time, materials such as gold nanoparticles, silver nanoparticles, MOFs, polymers, magnetic nanoparticles possess qualities that cannot be defined as quantum dots. However, these materials can be intertwined with quantum dots and create hybrid nanocomposites that increase signal amplification, charge transfer, adsorption, catalytic process, and etc (Chen et al., 2026) It is imperative to differentiate the QD materials from other complementary nanomaterials present in the various hybrid sensing architectures as metals such as gold nanoparticles (AuNPs), silver nanoparticles (AgNPs) or metal-organic frameworks (MOFs), do not qualify as QDs as they do not fall under the definition of the quantum-dot materials. However, they can certainly be combined together with QDs in order to make hybrid applications with superior sensing properties. The use of gold nanoparticles and silver nanoparticles results in localized surface plasmon effects and enhanced charges as well as their ability to amplify the signal. On the other hand, MOFs help to provide a wide range of adsorption sites, high surface areas as well as different catalytic or confinement effects. Hence any study that has used either gold nanoparticles, silver nanoparticles or metal-organic frameworks is regarded as a QD study only when it incorporates QDs in its work; otherwise these studies cannot be classified as QD based applications (Kalita et al., 2026). AgxSe QDs have been employed as signal amplifiers in spectroscopy for environmental monitoring, with a maximum signal enhancement of 38-fold for detecting pollutants in aquatic systems. Despite these benefits, heavy metal QDs raise concerns related to toxicity, environmental persistence, and the possibility of bioaccumulation, which constrains their application in food-related contexts. Green QDs, especially carbon quantum dots (CQDs) and graphene quantum dots (GQDs), have therefore been proposed as more environmentally friendly alternatives. Green QDs are typically produced using natural or waste-derived materials, exhibit low toxicity, and show high biocompatibility and sustainability in production. CQDs provide strong fluorescence, good water solubility, and abundant surface functional groups, which makes them suitable for sensor applications (Pinto et al., 2026). An example is the CQDs co-doped with nitrogen and phosphorus that had a detection limit of 0.016 ·/mL with high accuracy (98.78) in environmental analysis, which indicated their high analytical performance (Alqahtani et al., 2026). CQDs prepared via green synthesis have also shown significant stability and sensitivity for detecting heavy metal ions such as Cu2+, with detection limits in the nanomolar range (3–4.7 × 10^{-1} M as reported) (Akshaya and Shankaran, 2026). In food systems, green QDs can also be used to identify contaminants such as pesticides, antibiotics, and toxins while remaining safe for human consumption. CQDs integrated into sensing platforms have achieved detection limits of 0.40 μM for pesticide

Table 3
Comparison of heavy metal-based and green quantum dot (QD) systems for sensing applications, including composition, detection mechanisms, analytical performance, and associated advantages and limitations.

Category	QD System	Composition / Type	Target Analyte / Application	Detection Mechanism	Analytical Performance (LOD / Range / QY)	Stability / Advantages	Limitation	Reference
Heavy Metal QDs	CdSe QDs	II–VI semiconductor	Ochratoxin B (food toxin)	Fluorescence quenching	LOD: 0.016 μg/L; Range: 0.037–48 μg/L	High sensitivity; strong selectivity	Toxicity concerns	(Chen et al., 2026)
Heavy Metal QDs	CdTe QDs	II–VI semiconductor	Antibiotics (FQs)	Ratiometric fluorescence	LOD: 3.69–8.70 nM	Multiplex detection; high accuracy	Environmental risk	
Heavy Metal QDs	ZnSe/CdSe QDs	Core–shell QDs	Picric acid sensing	Fluorescence quenching	LOD: 1040 nM; Color purity: ~77%	Optical stability; LED compatibility	Cd toxicity	(Kalita et al., 2026)
Heavy Metal QDs	AgxSe QDs	Metal chalcogenide	Pharmaceutical pollutants	SEIRA enhancement	Signal ↑ 38 ×; LOD: 113,000 nM	Signal amplification; high sensitivity	Complex synthesis	(Pinto et al., 2026)
Heavy Metal QDs	CdTe QDs	Semiconductor QDs	Antibiotic residues	Fluorescence sensor	LOD: 4.7–13.1 nM; Recovery: 91–110%	High reproducibility	Toxicity	(Yin et al., 2026)
Heavy Metal QDs	CdSe/ZnS QDs	Core–shell	Norfloxacin detection	LMCT mechanism	LOD: 0.53 μg/kg (food matrix; do not convert)	Fast detection (5 min); portable	Heavy metal risk	(Chen et al., 2026)
Heavy Metal QDs	CdTe QDs + MOF	Hybrid nanosensor	Amyloid biomarkers	Photoelectrochemical	LOD: 0.0000031 ng/L	Ultra-high sensitivity	Biomedical limitation	(Wang et al., 2026)
Green QDs	N,P CQDs	Doped carbon QDs	Environmental drugs	Static quenching	LOD: 16 μg/L; Accuracy: 98.78%	Eco-friendly; high precision	Lower QY vs Cd-QDs	(Alqahtani et al., 2026)
Green QDs	Biomass CQDs	Waste-derived carbon	Food safety & packaging	Fluorescence sensing	Not applicable	Sustainable; biocompatible	Moderate sensitivity	(Rastegarpour et al., 2025)
Green QDs	CQDs (Hibiscus)	Plant-derived	Cu^{2+} detection	Fluorescence	LOD: 4.7 nM	Low cost; portable sensor	Selectivity limits	(Akshaya and Shankaran, 2026)
Green QDs	Boronic CQDs	Functionalized CQDs	Fe^{3+} detection	"On–off–on" fluorescence	LOD: 252 nM; QY: 55.48%	High QY; multifunctional	Complex synthesis	(Chen et al., 2026)
Green QDs	CQDs hydrogel	Polymer composite	Pesticide (MP)	Ratiometric fluorescence	LOD: 400 nM; Recovery high	Reusable; stable	Slightly higher LOD	(Li et al., 2026)
Green QDs	Graphene QDs	GQD	Dopamine/ serotonin	Dual-mode sensing	LOD: 0.6–1.1 nM	High sensitivity; low toxicity	Complex fabrication	(Singh et al., 2026)
Green QDs	N-doped CQDs	Biomass-derived	Gallic acid (food)	Fluorescence quenching	LOD: 38 nM; Recovery: 88–102%	Stable; anti-interference	Lower sensitivity vs Cd-QDs	(Zhong et al., 2025)

Note: To facilitate comparison, detection limits are reported in standardized units wherever possible. Mass-based values are expressed in **μg/L** (or **ng/L** for ultra-trace concentrations), while molar concentrations are expressed in **nM**. Food residue values are retained in **μg/kg** because they refer to solid matrices rather than liquid samples.

residues and have shown high recoveries (82–103%) for real food samples, demonstrating reliable analytical performance (Liu et al., 2026; Zheng et al., 2025). Furthermore, biomass-derived CQDs improve sustainability and reduce environmental impact without sacrificing fluorescence and sensing capabilities (Rastegarpour et al., 2025). A comparative overview of heavy metal and green QD-based sensing systems and their analytical performance is provided in Table 3. The analysis of the various quantum dot systems reveals that none is universally best for all pesticide sensing applications. The fluorescence quantum yield, narrow emission spectrum, and excellent photostability of cadmium based QDs make them particularly attractive for ultra-sensitive detection. But the issue of heavy metal toxicity and environmental persistence is not yet negligible for their use in food and water monitoring. Carbon and graphene quantum dots, however, have been found to be very biocompatible and environmentally safe, and they may be easily functionalized, with a less efficient fluorescence and analytical sensitivity than semiconductor QDs. Surface engineering, heteroatom doping and formation of Hybrid QD nanocomposites enhance sensor performance by increasing the florescent stability of quantum dots, support in charge transfer, increases active sensing sites density, and minimize fluorescence quenching, which eventually improves the sensitivity and selectivity of QD-based pesticide nanosensor.

4.4. Linking quantum dot properties to sensing performance

The physicochemical characteristics of quantum dots discussed in

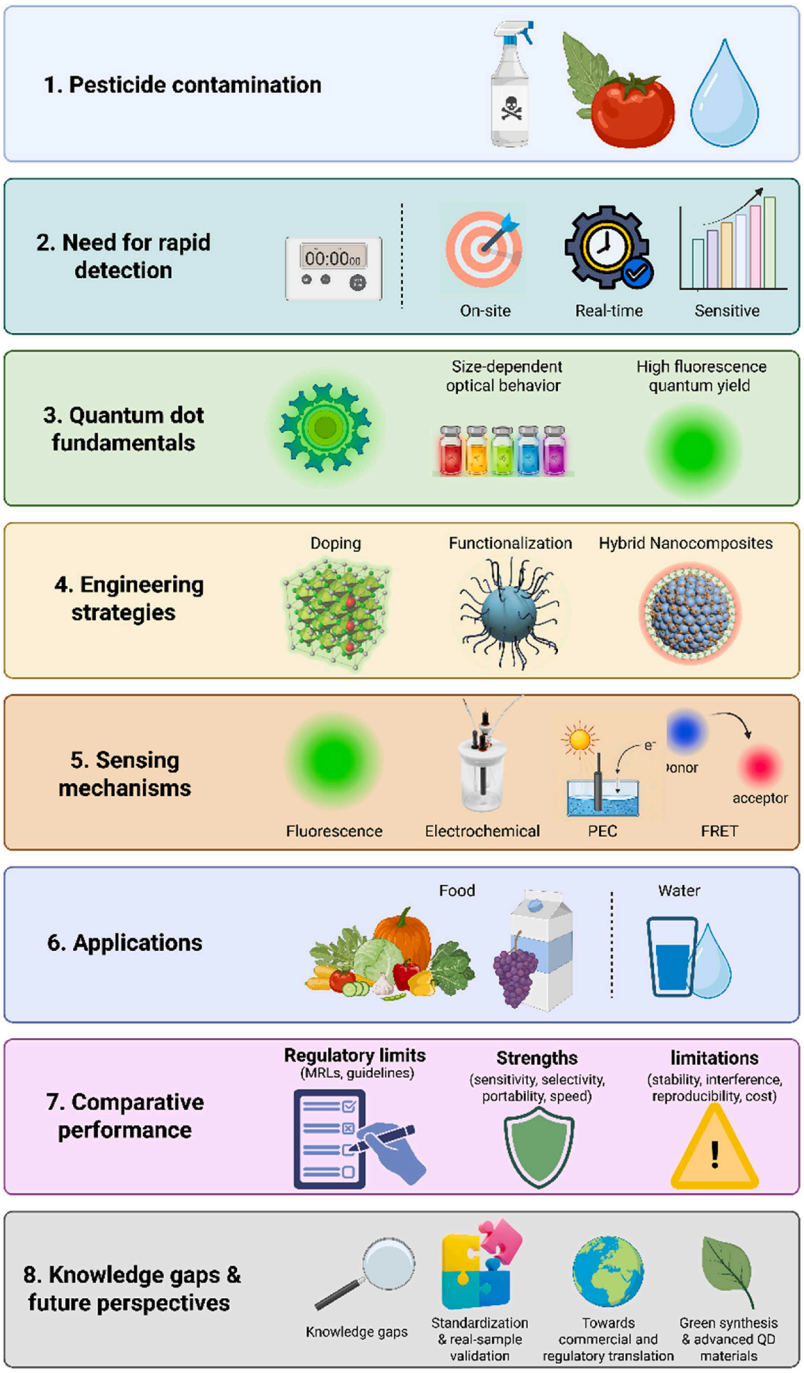


Fig. 5. Organizational framework of the review, illustrating the progression from pesticide contamination and quantum dot fundamentals to engineering strategies, sensing mechanisms, comparative performance evaluation, and future translational perspectives.

this section serve as the basis for their use in pesticide sensing. Factors such as quantum confinement, size-dependent optical properties, high fluorescence quantum yield, tunable emission wavelength, wide surface-to-volume ratio, and the ability to functionalize surfaces directly affect signal production, analyte detection, and sensor sensitivity (Algar et al., 2011; Wegner and Resch-Genger, 2024). These properties determine how different materials can serve in fluorescence, electrochemical, photoelectrochemical, and Förster resonance energy transfer (FRET)--based sensing platforms (Algar et al., 2019; Qureshi et al., 2023). Also, methods like heteroatom doping, surface passivation, and formation of hybrid nanocomposites adjust charge transfer and optical stability, thus affecting the overall performance of the analysis (Monsalve et al., 2024; Zhao et al., Nov 2024). Therefore, knowledge of the connection between the properties of quantum dots and the mechanisms of sensing creates a basis for the engineering approaches and comparative studies presented in the next sections. Fig. 5 provides an overview of the organizational framework of this review.

4.5. The toxicity and environmental safety of quantum dots based on heavy metals

Heavy metal-based quantum dots (QDs) such as cadmium, lead or mercury are exceptional in their optical properties and their high analytical sensitivity, but pose serious questions about environmental safety and health impacts. These nanomaterials may release toxic metal ions that increase the risk of cytotoxicity, oxidative stress, inflammation and damage to DNA which can affect aquatic organisms and other living systems under oxidative, acidic or photoinduced degradation conditions. The ability to be taken up by cells is also enhanced due to their small size, and concerns have been raised about their persistence in the environment and biomagnification in food chains over the long term (Giroux et al., 2022; Hardman, 2006).

The toxicity of QDs is not just related to their elemental composition but also to their particle size, surface chemistry, stability of the coating, and degradation. Surface defects or incomplete passivation can enhance the leakage of metal ions, while an increase in the chemical stability can be achieved by using a stable core–shell structure (such as CdSe/ZnS) or by coating the surface with a polymer and/or silica layer, thereby significantly reducing the leakage of metal ions. However, these methods do not completely mitigate the potential environmental hazards, especially following long-term exposure to the environment or disposal (Medintz et al., 2005). After being released into nature, the prospects of heavy metals in quantum dots (QDs) depend on a range of physicochemical aspects, including the values of pH, ionic strength, sunlight influence, the amount of dissolved organic material, and microbial activity. These aspects impact the processes of nanoparticle agglomeration, dissolution, oxidation, and transformation in the environment, resulting in the possibility of the toxic metal ions being released in both water and land ecosystems. Therefore, QDs may travel with the movement of water through the soil and sediment and absorbed by microorganisms, plants, and animals, thus being hazardous in terms of accumulation with QD-based technologies. Hence, it is important to understand these processes to evaluate QD technologies from the perspective of environmental hazards. Since these drawbacks have become increasingly apparent, other environmentally friendly alternatives, such as carbon quantum dots (CQDs), graphene quantum dots (GQDs), silicon quantum dots (SiQDs), and others, have been developed to address these concerns. While the overall toxicity and biocompatibility of these alternatives is low, they can also have low fluorescence quantum yields or may have less analytical sensitivity than traditional semiconductor QDs. However, advances in the dopant doping, defect management, surface stabilization, and hybrid nanocomposites preparation have greatly improved the optical performance of carbon-, graphene- and silicon-based QDs, thus making these environmentally friendly nanomaterials appropriate for food safety and environment monitoring as, in most instances, the lower toxicity and acceptance by regulators matter more than having the highest fluorescence intensity. Therefore, the current research is shifting towards the optimization of the surface functionalization, heteroatom doping and engineering of hybrid nanocomposites with high sensing performance and reduced environmental impact (Baker and Baker, 2010; Hola et al., 2014). Just as important as their proper use, the sustainable application of QD-based nanosensors requires consideration of their disposal and end-of-life management. Nanosensors that incorporate QDs derived from Cd, Pb and Hg are classified as hazardous lab waste and should thus be dealt with accordingly. Several methods can be considered to minimize the leakage of any nanoparticles during their use and disposal, and they include but are not limited to encapsulating QDs in stable polymer or silica structures, immobilizing them on reusable sensors and recovering or recycling the sensing materials used. Life-cycle assessment is yet another approach worth considering during the design of QD sensors as it ensures that regardless of the QD-based sensors being used, the environmental effect of their manufacture, operation and disposal is minimized.

In terms of application, it is highly desirable to develop more sustainable pesticide nanosensors based on QD by using green synthesis techniques, biodegradable materials, solvent-free methods of fabrication, and life-cycle assessment. To commercially launch QD-based sensors in a safe manner, several measures ought to be in place. Future regulations are likely to require that assessments of environmental fate of nanoparticles including migration, persistence, disposal, and the effect of these particles on human beings be carried out prior to using QDs in food monitoring and environmental testing. (Sakuratani et al., 2018; Tunali et al., 2025). The comparative Table 4 gives an overview of the different QD materials, their performance, safety and the potential for use.

Significantly, selecting the material for quantum dots should not be simply based on achieving the highest analytical sensitivity. Rather, the process of developing pesticides based on QDs must follow the safe-by-design principle, which allows for taking into account the optical properties, analytical sensitivity, environmental safety, potential human health risks, acceptability from the regulatory perspective and sustainability of relevant materials at the same time. Being considered from this point of view, green quantum dots might be better suited for routine food safety and environmental monitoring applications, despite the fact that their fluorescence performance can be relatively lower compared to traditional Cd-based QDs. The specific analytical ability of QD-based nanosensors arises mainly from the inherent physicochemical characteristics of quantum dots, such as their size-dependent band-gap characteristics, high fluorescence quantum yield, broad excitation spectra, narrow emission spectra, high photostability, and chemical tunability of the surface. Thus, the unique aspects of QDs are the basis for explaining how materials engineering, sensing principles, hybrid nanocomposite design, and architecture of the device affect the sensitivity, selectivity, stability, and feasibility of such sensors. Therefore, all the below-discussed points will be done from the perspective of QDs and will highlight their role in developing advanced pesticide nanosensors without discussing nanosensor technology in general (Farzin and Abdoos, 2021; Yadav et al., 2025).

5. QD-based signal transduction mechanisms

5.1. Fluorescence-based sensing

The fluorescence-based sensing method is one of the most common signal transduction techniques in quantum dot (QD) pesticide determination, considering the impressive optical behavior of QDs, their high quantum yield of fluorescence, precise emission spectrum, wide excitation range, and strong resistance to photodegradation. According to the mechanism of sensing, fluorescence signals can be changed through fluorescence quenching, fluorescence amplification, photoinduced electron transfer, or Förster resonance energy transfer (FRET). FRET is

Table 4
An assessment of the representative quantum dot materials in terms of their optical characteristics, toxicity, respect for the environment, disposal practices, fate in nature and usefulness in the area of food and environmental sensors.

QD Material	Optical Performance	Toxicity	Environmental Safety	Disposal Considerations	Environmental Fate	Recommended Applications	Representative References
CdSe/CdTe QDs	Excellent	High	Release of Cd^{2+} ions under oxidative, acidic, or photoinduced degradation; potential bioaccumulation	Low	Laboratory research; proof-of-concept sensing	**CdSe/CdTe QDs**	(Derfus et al., 2004; Hardman, Feb 2006)
Pb-based QDs	Excellent	High	Pb^{2+} ion release; environmental persistence and ecological toxicity	Low	Specialized sensing requiring NIR optical properties	**Pb-based QDs**	(Akkerman et al., 2018; Kovalenko et al., 2017)
Carbon QDs (CQDs)	Good	Very low	Negligible toxic ion release; biodegradable with low environmental persistence	Excellent	Food and water monitoring; portable and sustainable nanosensors	**Carbon QDs (CQDs)**	(Baker and Baker, Sep 10 2010; Hola et al., 2014)
Graphene QDs (GQDs)	Good	Very low	High chemical stability with minimal degradation products; low bioaccumulation	Excellent	Biosensors, environmental monitoring, food safety	**Graphene QDs (GQDs)**	(Hola et al., 2014; Li et al., 2013)
Silicon QDs (SiQDs)	Moderate	Low	Slow oxidation to relatively benign silica products; environmentally compatible	Excellent	Biomedicine, environmental sensing, food analysis	**Silicon QDs (SiQDs)**	(Dasog et al., 2016; Li et al., 2013)
InP QDs	Good–Excellent	Low	Minimal metal-ion leaching compared with Cd-based QDs; improved chemical stability	Good	Biosensors, food safety monitoring, bioimaging	**InP QDs**	(Kareem et al., 2026)

not a distinct sensing modality but a fluorescence-based energy-transfer mechanism. It involves non-radiative transfer of excitation energy from a donor fluorophore to a nearby acceptor over nanometer-scale distances. Therefore, in this paper, FRET-based sensors are described as a type of fluorescence sensing mechanism (Algar et al., 2019; Hildebrandt et al., Jan 25 2017). Building on the fundamental properties of QDs, this section examines how different signal transduction mechanisms convert material characteristics into analytical performance. Nanosensing of pesticide residues in food and water using fluorescence-based quantum dots (QDs) is an effective approach owing to its high sensitivity, rapid response, and ability to operate in complex systems. The main fluorescence-based mechanisms include fluorescence quenching, Förster Resonance Energy Transfer (FRET), and the inner filter effect (IFE). Fluorescence quenching is among the most widely used models, in which the fluorescence intensity of QDs decreases upon interaction with pesticide molecules. Quenching can occur via static or dynamic pathways, including mechanisms involving energy donation or charge transfer. For example, nitrogen-doped graphene quantum dots exhibited a detection limit of 0.274 nM and recovery of 94–103% for antibiotic residue detection in food under static quenching (Hui et al., 2026). Metal ions have also been detected using perovskite QDs via turn-on/turn-off fluorescence behavior, enabling detection limits as low as 0.21 nM (Pang et al., 2026).

Carbon QDs likewise demonstrated quenching-based sensing of food contaminants with high stability and selectivity (Lin et al., 2026). QD-based nanosensors have been used to detect pesticides with quenching, providing quick response times and high anti-interference performance (Yang et al., 2026). Collectively, these findings confirm that quenching-based systems are suitable and sensitive tools for detecting trace pesticides. Another major fluorescence process is Förster Resonance Energy Transfer (FRET), which involves non-radiative energy transfer between a donor QD and an acceptor molecule when they are in close proximity. FRET enables high sensitivity and ratiometric analysis of pesticides. For instance, a QD-based ratiometric fluorescence sensor utilized analyte-induced changes in the efficiency of FRET to detect an analyte at a limit of 0.67 U/L in complex samples (Ning et al., 2026). MXene quantum dots have further shown that FRET can account for 47.1% of the quenching process in pollutant determination, with a detection level of 17 nM (Han et al., 2026). Dual-mode QD systems combining FRET with other mechanisms have also been demonstrated for food safety monitoring, enabling rapid analysis (<30 s) and sensitive detection of analytes (Yang et al., 2026). FRET-based sensors are particularly beneficial for pesticide detection because of their high selectivity and their ability to reduce background interference. A commonly used mechanism is the inner filter effect (IFE), in which the analyte absorbs excitation or emission light, thereby lowering the fluorescence intensity without direct interaction with QDs. Carbon QDs have found broad applications in IFE-based sensing. For example, CQDs identified food substances with a detection limit of 0.061 nM and recovery values of 94.8–104.8% (Cai et al., 2026). Silicon QDs have also been shown to provide IFE-based quenching with the lowest detection limit for milk samples of 8 pM (Chacko et al., 2025). In addition, QD-based dual-mode IFE biosensors were capable of detecting pathogens at limits as low as 0.54 CFU/mL with high sensitivity (Liu et al., 2026). In remote pesticide monitoring, IFE can support simple, fast, and cost-efficient detection strategies, particularly in field-deployable and portable systems. The key sensing mechanisms of QD-based nanosensors, Fig. 6 illustrates that fluorescence utilizing QD nanosensors works with a few steps, including fluorescence quenching, fluorescence enhancement, and FRET. The Fig. further indicates the importance of surface modification and target identification in the process of signal production and analytical sensitivity.

5.1.1. Fluorescence quenching

The quenching of fluorescence is the most popular signal transduction method used in QD-based pesticide nanosensors because of its simplicity, fast response and high analytical sensitivity. The idea behind this strategy is that the fluorescence intensity of quantum dots becomes less when they interact with the pesticide molecule or the recognition event that occurs. Depending on the physicochemical properties of the analyte and the nanomaterial interface, quenching can proceed by dynamic (collisional) or static (complex formation) processes, as well as by inner filter effect (IFE), electron transfer or energy transfer processes. The characteristics of QDs such as high quantum yield, narrow emission spectrum and excellent photostability allow highly sensitive fluorescence measurements with low detection limit. However, even in very complex food and environmental samples, optical interference, nonspecific adsorption, and matrix autofluorescence can compromise the analytical accuracy and, in order to increase the confidence, surface passivation and selective recognition strategies must be used to overcome these problems (Algar et al., 2011; Lakowicz, 2006; Medintz et al., 2005; Resch-Genger et al., Sep 2008).

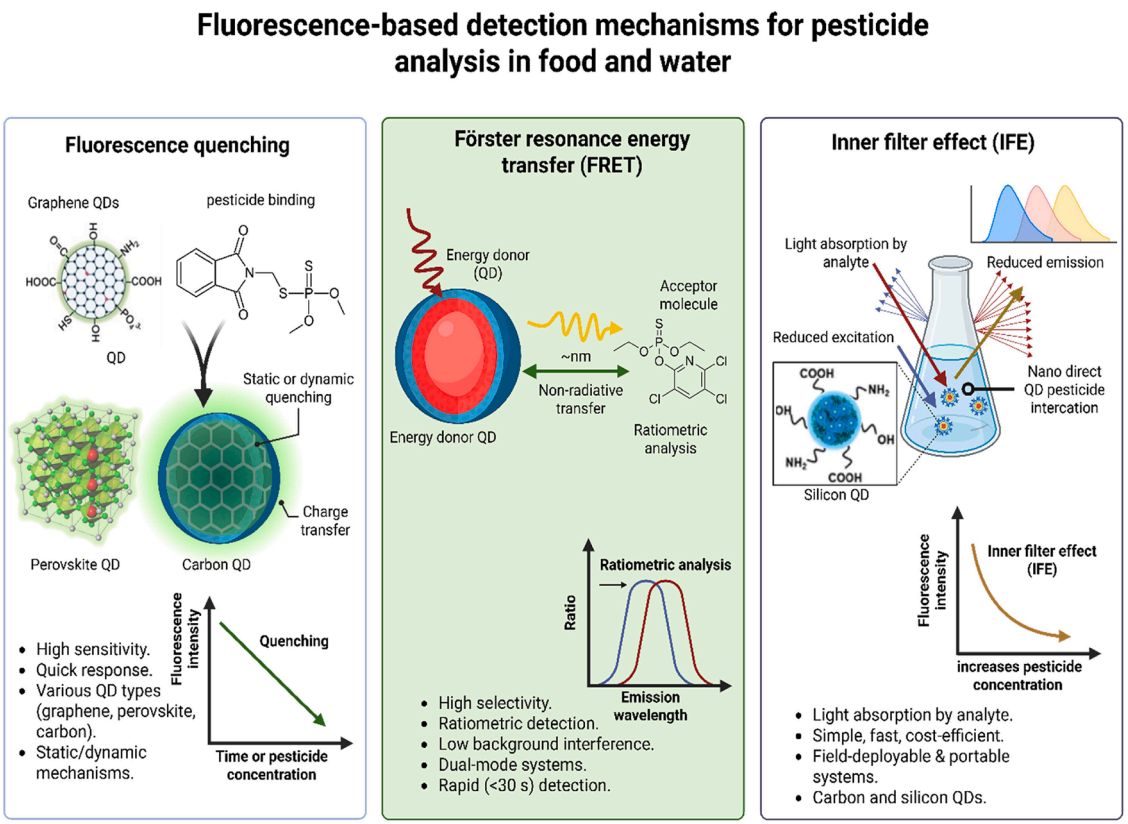


Fig. 6. Schematic illustration of quantum dot-based sensing mechanisms, highlighting Förster resonance energy transfer (FRET), fluorescence quenching, and ratiometric detection for ultra-sensitive analyte monitoring.

5.1.2. *Fluorescence enhancement*

In contrast to quenching, the basis of fluorescence enhancement is an increase in the emission intensity of the QD after the recognition of the analyte. Enhancement is usually due to the suppression of non-radiative recombination processes, passivation of surface defects, or reactivation of surface defects after reacting with quencher. This sensing approach typically yields high signal to background ratios, enhanced sensitivity to background interference, and is well suited for detection of trace levels of pesticides in complex matrices. Fluorescence enhancement mechanisms, however, are in general more system specific and rely intimately on the surface chemistry of the QD, the chemistry and structure of the ligands, and the recognition elements involved to obtain repeatable analytical performance (Chen et al., 2016; Medintz et al., 2005).

5.1.3. *Förster resonance energy transfer (FRET)*

Förster resonance energy transfer (FRET) is a very sensitive fluorescence-based mechanism that involves non-radiative transfer of excitation energy between a donor and an acceptor positioned about 1-10nm apart. The efficiency of the energy transfer is highly sensitive to the intermolecular distance, which allows highly selective molecular recognition and real-time detection of the binding events that occur as a result of pesticide exposure. These properties of quantum dots make them particularly effective FRET donors: the absorption spectrum is broad, the emission spectrum is narrow and can be size-tuned, they are highly photostable and immune to photobleaching. These benefits make for multiplex detection and quantitative biosensing. But, the fabrication of the probe is rather complex in order to achieve precise control of donor/acceptor spacing, spectral overlap, and probe architecture, to achieve accurate FRET sensing (Algar et al., 2019; Hildebrandt et al., Jan 25 2017; Medintz et al., Sep 2003; Sun et al., 2013).

5.1.4. *The process of photoinduced electron transfer (PET)*

Another important mechanism of modulation of fluorescence is photoinduced electron transfer (PET) which is used in nanosensors that use QDs. When the photoexcited quantum dot is coupled with an electron donor or electron acceptor, the direction and efficiency of the transfer gives rise to either fluorescence quenching or enhancement. The electronic structure of QDs, band-edge alignment, surface functional groups and the redox properties of pesticide molecules play significant roles in PET processes. Modifications like heteroatom doping, surface modification, and hybridization with conductive nanomaterials are very important in engineering to enhance the electron transfer efficiency and sensitivity of the sensor. This has sparked a lot of interest in using PET-based QD nanosensors for the highly specific and sensitive detection of pesticides in food and environmental monitoring (de Silva et al., 1997; Qureshi et al., 2023).

5.2. *Electrochemical and photoelectrochemical sensing*

Electrochemical and photoelectrochemical (PEC) sensors are used to detect nitrite and nitrate, among other compounds. These approaches are applied to the detection of nitrite and nitrate, as well as other analytes. PEC and electrochemical (EC) sensing strategies are especially suitable for analyzing pesticide residues in food and water because they provide high sensitivity and fast signal response and can be implemented with portable devices. Such systems rely on efficient signal transduction, conversion of biochemical interactions into measurable electrical signals or photocurrent signals, and signal amplification, thereby increasing sensitivity to ultra-trace concentrations.

Electrochemical sensing involves a biochemical interaction that produces an electrical response, which can be measured as current, potential, or impedance. For example, an electrochemical biosensor based on dsDNA detected malathion in contaminated food through

changes in a redox signal, achieving a limit of detection of 5 pmol/L with high selectivity (Elshafey et al., 2026) Electrochemical sensors based on graphene quantum dots improved electron transfer efficiency, enabling detection of methyl parathion with a detection limit of 0.01 nM in water and fruit samples (Pengsook et al., 2026) Further, aptamer-based electrochemical sensors exploit catalytic strand displacement amplification, yielding detection limits of 0.054 nM for fipronil in cabbage samples (Liu et al., 2025). Moreover, alloy nanomaterials with high entropy demonstrated increased catalytic redox reaction activity, providing ultra-low detection limits of 1.47×10^{-9} M for acetamiprid and 3.18×10^{-9} M for omethoate, together with high signal amplification (Xu). In addition, electrode sensitivity was enhanced using gold nanoparticles, allowing detection of pesticides at the femtomolar level (Loguercio et al., 2025). These studies affirm that electrochemical sensing enables fast, portable, and highly sensitive detection of pesticides. Photoelectrochemical (PEC) sensing combines light excitation with electrochemical reactions to generate photocurrent signals, typically with low background noise and high sensitivity. For instance, a Pd/CdS/Co3S4 nanocage PEC sensor based on a MOF achieved a 4.63-fold increase in photocurrent and a 0.05 ng/mL detection limit for chlorpyrifos in water samples (Huang et al., 2025). Carbon quantum dot-modified TiO2 PEC sensors improved light absorption and charge transfer capability, enabling detection of triazophos with a detection limit of 0.03 nM in aqueous systems (Zeng et al., 2024). A nanozyme-centered PEC biosensor was characterized by high catalytic activity, with a detection limit of 50 pmol/L for organophosphate pesticides in mixed samples (Zuo et al., 2024). In addition, PEC systems based on heterojunctions enhanced charge separation efficiency and showed detection ranges of 0.05–500 ng/mL with superior stability (Wang et al., 2022). PEC biosensors based on QDs have also been reported to achieve very high sensitivity, with detection limits of 10^{-4} M for pesticide residues in food matrices (Li et al., 2015). Overall, these findings suggest that PEC sensing has strong potential for real-time environmental monitoring. Electrochemical and photoelectrochemical sensing approaches for pesticide detection are illustrated in Fig. 7.

5.3. Recognition mechanisms

The performance of QD-based nanosensors depends on recognition mechanisms that determine selectivity and sensitivity toward pesticide residues in complex food and water environments. Key recognition mechanisms employed in QD-based nanosensors are illustrated in Fig. 8. Three widely used strategies include enzyme inhibition, aptamer-based recognition, and antibody-based sensing. Enzyme inhibition, particularly acetylcholinesterase (AChE), is a well-established method for sensing organophosphorus pesticides. These pesticides cause AChE inhibition, leading to signal changes. Biosensors using AChE have proven to be highly sensitive and suitable for portable monitoring of food and environmental samples (Zhang et al., 2025). Organophosphorus pesticides and carbamates are important pesticides recognized for their ability of enzyme inhibition, especially of acetylcholinesterase (AChE). In the case of QD based nanosensors, the inhibition of AChE can be correlated with the optical or electrochemical characteristics of the QDs, and this inhibition can be detected. In vegetable and fruit samples, for

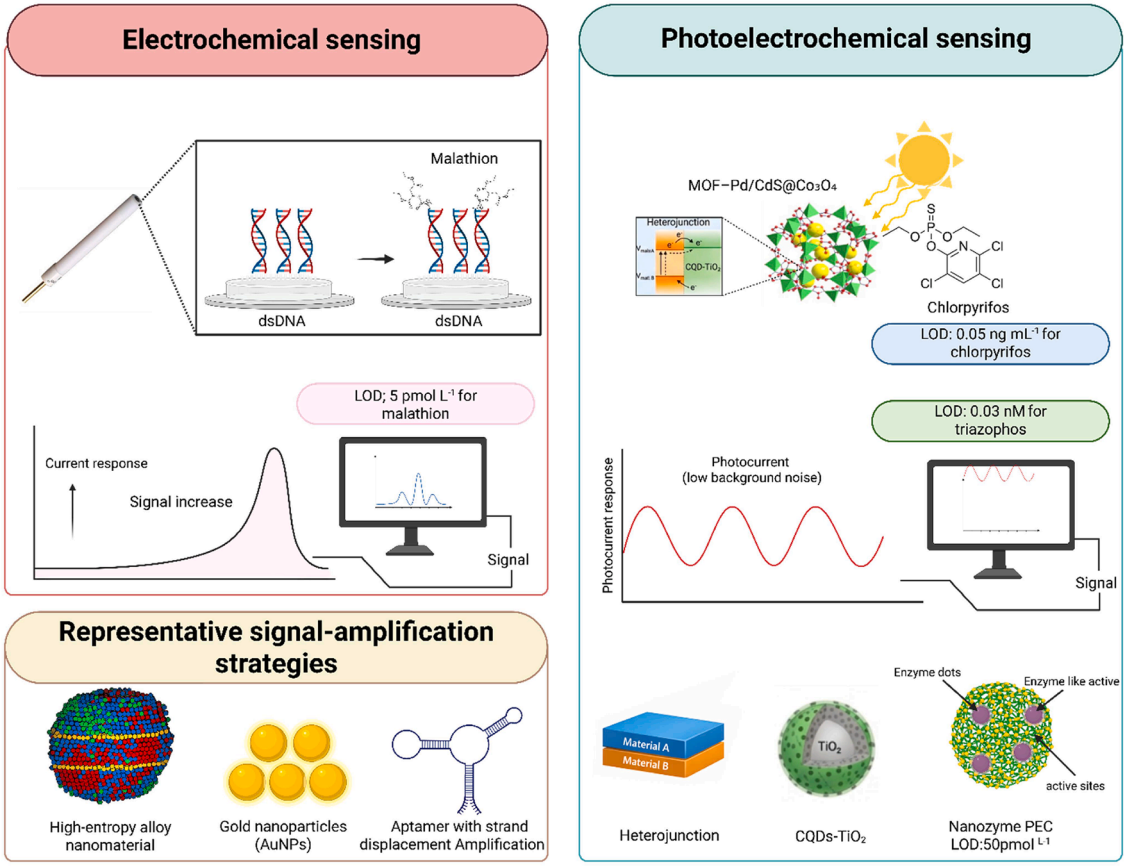


Fig. 7. Schematic comparison of electrochemical (EC) and photoelectrochemical (PEC) strategies for pesticide detection and representative signal-amplification approaches. In EC sensing (left), pesticide recognition at DNA- or aptamer-modified electrode interfaces generates changes in electrical responses, while nanomaterial-assisted electron transfer and amplification strategies, including high-entropy nanomaterials, Au nanoparticles, and strand-displacement amplification, enhance analytical sensitivity. In PEC sensing (right), light-excited photoactive nanostructures, including Pd/CdS@Co_3S_4 and CQD–TiO_2 architectures, generate pesticide-dependent photocurrent responses, whereas heterojunction and nanozyme-assisted systems improve charge separation and catalytic signal amplification. Representative sensing architectures and analytical performances shown in the schematic correspond to the systems discussed in Section 4.2.

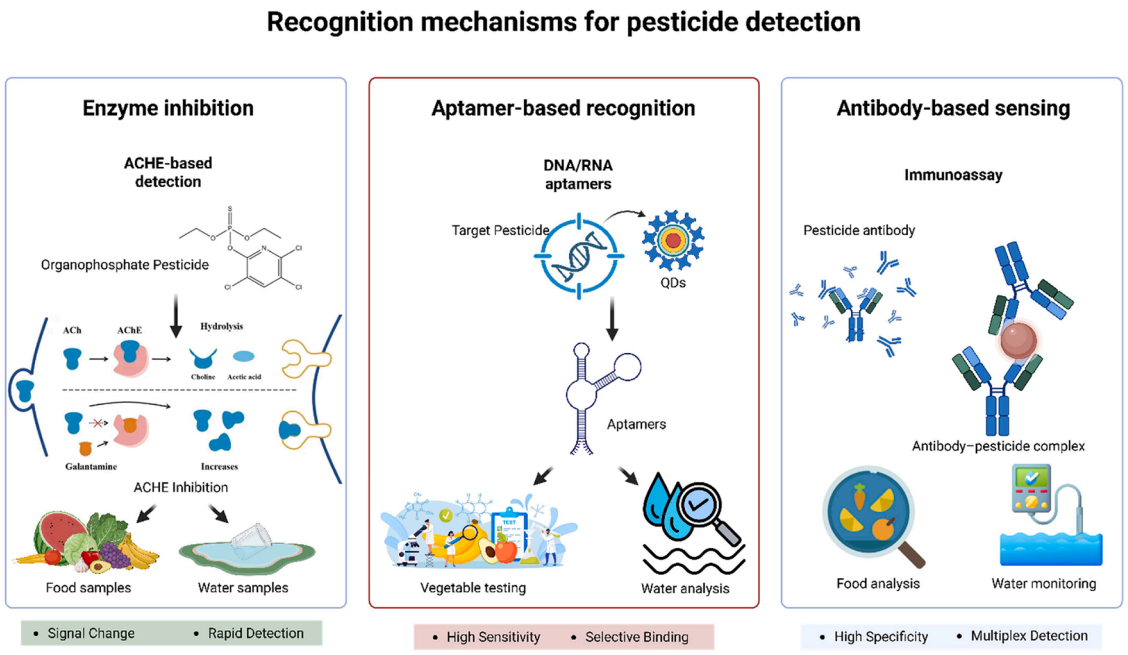


Fig. 8. Recognition mechanisms in quantum dot-based nanosensors, including enzyme inhibition, aptamer-based binding, and antibody-based immunoassays for selective pesticide detection in food and water systems.

instance, detection of organophosphorus pesticides like paraoxon and parathion in the low picomolar range (Zheng et al., Feb 15 2011) has been achieved using CdTe QDs incorporated in an AChE. A comparable detection system, based on graphene quantum dot (GQD)/AChE/choline oxidase, was used to detect dichlorvos using the enzyme-inhibition sensing method, which showed the potential of the GQD-based enzyme-inhibition sensing technique for application in food, water, and environmental analysis (Sahub et al., 2018). Carbon quantum dots (CQD)–gold nanoparticles system has also been developed for the detection of paraoxon, malathion, methamidophos and carbaryl in water and apple juice samples in the presence of AChE inhibition and reactivation. It has recently been reported that a sulfur-doped CQD-based fluorometric sensor using AChE is able to detect malathion and chlorpyrifos at concentrations of 1.70 and 1.50 ppb, respectively (Korram et al., 2019). The studies summarized here show how AChE can be successfully combined with QD as a signal reporter, thus offering a relevant recognition strategy for QD-based pesticide nanosensors. Portable strip biosensors also registered detection limits of 6.57 ng/mL for organophosphates in agricultural products and lake water (Luo et al., 2025). The application scope of these systems is broad in food safety (vegetables and fruits) and water monitoring owing to rapid response times and low costs. Aptamers are highly specific and high-affinity synthetic single-stranded DNA or RNA molecules that target pesticides. They offer chemical stability, reusability, and straightforward chemical modification. Nanosensors made with aptamers have demonstrated ultra-high sensitivity, with detection limits reaching the femtomolar range in food samples (Zhu et al., 2026). Likewise, an isofenphos-methyl lateral flow aptasensing kit enabled detection at 12.61 nM, with recovery of 90.67–104.63% in vegetables. A malathion dual-mode aptamer–nanozyme system achieved recoveries of 92–107% for malathion in food and environmental samples (Nie et al., 2026). Moreover, FRET-aptasensors exhibited a 2.8 pM detection limit in food matrices for acetamiprid (Gholami et al., 2025). Such systems are well suited for pesticide monitoring in food and water because they are selective and adaptable to different sensing platforms. Antibody-based sensing relies on antigen–antibody interactions. Immunosensors are reliable and follow established procedures, which supports their extensive use in food safety applications. For example, microsphere flow cytometry enabled detachment and detection of pesticides in food samples with a detection limit at the attogram level (Ying et al., 2025). A magnetic relaxation immunosensor detected chlorpyrifos in tomato and water samples, achieving a detection limit of 0.24 ng/mL (Dong et al., 2025). Additionally, antibody-modified microneedle sensors were able to detect difenoconazole in vegetables with a detection limit of 36.71 ng/mL (Chen et al., 2025). These systems demonstrate high applicability in real food matrices, supported by high recovery and reproducibility. Immunosensors are also increasingly combined with nanomaterials to amplify signal output and enable portable operation for field-based detection of water contaminants (Mendes et al., 2025). Enzyme inhibition, aptamer-based recognition, and antibody-based sensing are complementary strategies for pesticide detection. Enzyme systems are simple and fast for screening, Aptamers improve the specificity of QD-based sensors by explicitly controlling the interaction of pesticides with the fluorescence or electrochemical signals produced by QDs. Fig. 8 illustrates the main recognition mechanisms in quantum dot-based nanosensors, including enzyme inhibition, aptamer binding, and antibody-based immunoassays for selective pesticide detection. Comparing the reported detection mechanisms shows that each approach has its own unique benefits, depending on the application. The sensitivity of fluorescence-based sensors is typically good, with the lowest detection limits, and is highly selective, yet they are subject to possible matrix interference and fluorescence quenching in complex food samples. Electrochemical sensors offer high portability, speed of response and miniaturization capability, but have some problems regarding the fouling of their electrodes and their long-term stability. The disadvantage of photoelectrochemical sensors is that they need relatively complex fabrication procedures, and they have low background signals while they are very sensitive. FRET-based systems have good multiplexing capability, but require close donor–acceptor interaction. Future developments of sensors should thus embed complementary sensors to make them more robust and applicable to analysis.

5.4. Critical comparison of recognition strategies for practical pesticide detection

While enzyme inhibition, antibodies, aptamers and molecularly imprinted polymers (MIPs) are commonly used as recognition elements in QD-based nanosensors, other factors such as the intended application need to be considered in determining the analytical value of these elements beyond just the recognition mechanism. Therefore, the choice of a suitable recognition strategy should be based on a number of criteria including sensitivity, selectivity, operational stability, cost and appropriateness for the intended analytical purpose (Arduini et al., 2016; Berkal and Nardin, Oct 2023). It is especially advantageous for broad-spectrum screening because the same enzyme (e.g., acetylcholinesterase (AChE)) is inhibited by a variety of organophosphate and carbamate pesticides and tends to produce a response by inhibiting catalytic activity. This helps to quickly screen for possible pesticides without prior knowledge of the specific pesticide present. But, in most cases enzyme inhibition is not very selective, that is, chemically similar pesticides can have similar effects on the enzyme and confirmation by chromatographic methods or very selective biosensors is required (Arduini et al., 2016). Aptamer-based recognition is excellent, as the aptamers are designed to have high affinity for individual pesticide molecules giving molecular selectivity. They are synthesized in a straightforward way, are chemically stable, and can be easily modified and are useful for multiplex sensing and portable devices. However, there are pesticides for which aptamer selection is not available and sensor performance could be affected by the matrix composition and the ionic strength. Although other types of recognition strategies are now available, antibody-based immunosensors are still one of the most selective strategies and are especially useful for regulatory monitoring, where precise quantification of each of the individual pesticide residues is needed. They have a high affinity and they perform very well in complex samples but they are relatively expensive, cannot be stored in biological conditions for a long period and require careful storage conditions (Chen et al., Mar 6 2017). Molecularly imprinted polymers (MIPs) are very stable synthetic recognition materials, which are similar to the biological receptors, but with a much higher chemical and thermal stability. The advantages of MIPs are the reusability of the sensors and the ability to function in harsh conditions, but in general, the affinity is lower and the binding kinetics are slower than for antibodies or aptamers. There is no one best recognition strategy in general. Instead, enzyme inhibition is the method of choice for quick identification of pesticides at the class level, while aptamers and antibodies are best suited for highly selective detection of specific pesticides. In situations where robustness, low cost and long-term operational stability are desired, MIPs offer a desirable alternative (Wang and Shannon, Dec 5 2011). As shown in Table 5, the comparison of techniques of recognition in QD pesticides nanosensors is provided along with their specificity, applications, advantages, and limitations.

6. Engineering strategies for QD-based nanosensors

6.1. Surface engineering and selectivity enhancement

This section forms the core of the review by critically evaluating engineering strategies that govern the sensitivity, selectivity, stability, and practical applicability of QD-based pesticide nanosensors. Surface engineering is an important approach for improving the selectivity and sensitivity of quantum dot (QD)-based nanosensors for pesticide detection in food and water systems. Growing specific chemical groups (e.g., –COOH, –NH, and –SH) increases the affinity of analyte binding and enables efficient signal transduction. For example, carbon nanomaterials such as graphene and QDs offer high surface area and versatile functionalization, boosting electron transfer and enhancing the sensitivity of electrochemical sensors substantially (Aslam, 2026). Similarly, metal–organic frameworks (MOFs) provide active sites and scalable porosity, enabling selective adsorption of complex food matrices and signal amplification. Molecularly imprinted polymers (MIPs) enhance the capacity of QD-based sensors by introducing selective recognition cavities and keeping the unique luminescence properties of quantum dots intact. MIP-based sensors have demonstrated high selectivity and portability, particularly when combined with smartphone-based detection for on-site monitoring of food and water (Li et al., 2025). Moreover, click chemistry and surface modification strategies allow probes to be immobilized precisely, improving resistance to interference from complex matrices (Alam et al., 2026; Guo et al., 2026) and enabling defect-engineered MOFs to enhance catalytic activity and recognition of targets. As an example, AChE@AMOF enhanced enzyme activity by 3.4-fold and recognition efficiency by 5.6-fold, achieving a detection limit of 0.05 ng/mL paraoxon in food samples (Su et al., 2026). Similarly, nanozyme-based systems and hybrid nanocomposites enhance catalytic amplification and stability, enabling sensitive pesticide detection in aquatic environments (Sasikumar et al., 2025; Wang et al., 2025; Zhao et al., 2026). In addition, signal stability and accessibility are improved through interfacial engineering and nanoarchitecture design (e.g., hydrogel, aerogel, and thin-film platforms). For instance, hydrogel-based QD sensors achieved a detection limit of 0.108 ng/mL acetamiprid in tea samples, indicating strong applicability for food-system monitoring (Zhu et al., 2025). Overall, these approaches facilitate potent, selective, and field-deployable pesticide-monitoring nanosensors for food and water applications. Different QD materials are selected for soil and water monitoring according to their physicochemical properties and the requirements of the target matrix. Table 6 summarizes representative QD materials used in pesticide sensing in terms of sensing mechanism, detection limit, advantages, limitations, and practical applications, thereby enabling comparison of the trade-offs among analytical performance, safety, and practical applicability.

As indicated in Table 6, the selection of quantum dot (QD) materials requires the consideration of both the efficacy of the QD materials and

Table 5
A comparison of recognition strategies implemented in QD-based pesticide nanosensors, incorporating enzyme inhibition, aptamers, antibodies, and molecularly imprinted polymers (MIPs), so that it is possible to ensure that information is provided regarding specificity, applications, advantages, and disadvantages.

Recognition strategy	Recognition specificity	Best analytical application	Advantages	Limitations	Ref.
Enzyme inhibition	Low–Moderate	Broad screening of organophosphates and carbamates	Rapid, simple, inexpensive, class-wide detection	Cannot distinguish individual pesticides	(Andreou and Clonis, Jan 2002)
Aptamer	Very high	Selective detection of individual pesticides	High affinity, easy functionalization, multiplex capability	Aptamers unavailable for some analytes; matrix sensitivity	(Song et al., 2008)
Antibody	Very high	Regulatory monitoring and quantitative analysis	Excellent specificity, validated immunoassays	Expensive, lower storage stability	(Yusa et al., 2015)
Molecularly imprinted polymer (MIP)	Moderate–High	Portable, reusable, field-deployable sensors	Robust, low cost, chemically stable	Lower affinity and slower binding than biological receptors	(Wulff, 1995)

Table 6
Comparative characteristics of different quantum dot (QD) materials employed for pesticide sensing, including their dominant sensing mechanisms, representative detection limits, principal advantages, limitations, practical applicability, and representative references.

QD Material	Typical Sensing Mechanism	Representative LOD (nM)	Main Advantages	Main Limitations	Most Suitable Application	Practical Readiness	Environmental/ Toxicity	QD Material	Ref.
CdSe/CdTe QDs	Fluorescence, FRET, PEC	**0.0001–5**	Excellent fluorescence, high quantum yield	Heavy metal toxicity	Mainly laboratory research	High	Moderate	High concern	(Qureshi et al., 2023; Safari, 2022)
Carbon QDs (CQDs)	Fluorescence, Electrochemical	**0.5–20**	Low toxicity, green synthesis, easy functionalization	Lower quantum yield	Food and water monitoring	Excellent	High	Very low	(Murugesan et al., 2025; Tian et al., Mar 14 2023)
Graphene QDs (GQDs)	Fluorescence, Electrochemical	**0.2–10**	High conductivity, excellent stability	Moderate fluorescence	Portable biosensors	Excellent	High	Very low	(Kalluri et al., 2018; Kumar and Rhim, 2025; Tabish et al., 2022)
Silicon QDs (SiQDs)	Fluorescence	**5–100**	Biocompatible, environmentally friendly	Lower emission intensity	Biomedical and environmental sensing	High	High	Low	(Oyshi et al., 2024; Zhang et al., 2023)
Perovskite QDs	Fluorescence, PEC	**0.02–5**	Exceptional optical properties	Moisture instability, Pb toxicity	Emerging sensing platforms	Moderate	Moderate	High concern	(Ren et al., Jun 29 2022)
ZnS/ZnSe QDs	Fluorescence	**1–100**	Lower toxicity than Cd-based QDs	Lower sensitivity	Environmental monitoring	High	High	Low	(Kaushal et al., 2026; Yu and Liu, 2026)
Hybrid QD Nanocomposites	Fluorescence, Electrochemical, PEC	**0.00001–0.1**	Synergistic performance, enhanced selectivity	More complex fabrication	High-performance field-deployable sensors	High	Moderate	Composition-dependent	(Hooshiar et al., 2026; Zhao et al., Nov 2024)

their practical use, as illustrated by Cd-based QDs, which are recognized for having the highest level of fluorescence and detection limits, though their toxicity and regulatory restrictions limit their utilization. Carbon-, graphene-, and silicon-based QDs have less analytical performance than Cd-based QDs, but they are advantageous in providing better compatibility with the environment, stability, and the possibility of being used in everyday analysis of food and water. Hybrid QD nanocomposites illustrate the combination of benefits from different materials in order to achieve higher sensitivity and selectivity, but with the diminished simplicity of production.

6.2. *Hybrid nanocomposites*

Hybrid nanocomposites comprising quantum dots (QDs) and complementary nanomaterials are effective engineering approaches for improving sensitivity, selectivity, and signal gain in pesticide sensing in food and water systems. Recent advances in hybrid QD-based sensing systems and their analytical performance are summarized in Table 7. In this case, “hybrid QD nanocomposite” specifically refers to the system where QDs are a required factor in the design of the sensing architecture, while the other material is considered a complementary functional material. Thus, AuNPs, AgNPs, MOFs, conductive polymers, graphene-based materials and magnetic nanoparticles are referred to as supportive or functionalizing nanomaterials but not as QDs themselves. These hybrid systems exploit synergistic optical, catalytic, and electronic properties. Hybrid nanoparticles composed of QDs and metals particularly gold (AuNPs) and silver nanoparticles (AgNPs) yield substantial improvements through plasmonic interactions, enhanced electron transfer, and signal amplification. For example, AuNP-based QD systems enable efficient Förster resonance energy transfer (FRET), allowing detection of organophosphates at detectable nanomolar concentrations (Wahyudi et al., 2025) AgNP-functionalized MOF-QDs can also be used as co-reaction archetypes to promote electrochemiluminescence (ECL) signals, enabling malathion detection in food samples at ultra-low concentrations of 0.108 pM (Zhang et al., 2026). Metal-enhanced fluorescence (MEF) further improves signal intensity. In particular, AgNP-based MIP-QD systems enhanced fluorescence by more than 7.1-fold, enabling selective pesticide detection in food matrices (Xu et al., 2025). In addition, electrodes with AuNP-functionalities achieved a glyphosate detection threshold of 1.65 nM in water samples. The broad applicability of these hybrid systems for monitoring food (vegetables and fruits) and water is attributed to their high signal amplification and rapid response. QD–MOF nanocomposites combine the high surface area and tunable porosity of metal–organic frameworks (MOFs) with the optical characteristics of QDs, improving analyte capture and signal transduction. MOFs provide excellent adsorption and abundant active sites and enhance detection of food and environmental samples containing complex compounds (Wang et al., 2026). For example, IRMOF-3/CdTe QD composites exhibit strong ECL performance, reaching an ultra-low detection limit of 44.7 fM for pesticide residues in vegetables and river water (Gu et al., 2025) Moreover, AIE-MOF-QD systems enabled sensitive diazinon detection with a detection limit of 0.14 ng/mL in crops (Tang et al., 2025). MOF nanozyme-based systems enhance catalytic activity and signal amplification, achieving a detection limit of 0.06 ng/mL (Li et al., 2025). Further hybrid systems, such as Pd/CdS@Co3S4 QD–MOF nanocages, have been used to achieve a 4.63-fold photocurrent amplification and detection limits of 0.05 ng/mL in water samples (Huang et al., 2025). Collectively, these systems are valuable for food-safety surveillance and environmental testing. QD–polymer hybrid systems, including hydrogels and flexible matrices, exhibit improved stability, flexibility, and real-time sensing performance. These materials enable non-destructive on-site detection in complex matrices (food surfaces and aquatic environments). For instance, starch-based hydrogel–QD systems exhibited an adsorption energy of 65.3 kcal/mol and enabled methyl parathion detection at 0.40 μM. Notably, a DNA–AgNP hydrogel sensor achieved a limit of detection

Table 7
Advanced quantum dot-based hybrid sensing systems for pesticide detection, highlighting different nanocomposite strategies, matrices, and ultra-sensitive analytical performance.

Hybrid System	Key Analytical Benefit	Tradeoff (Added Complexity)	When Hybridization Is Justified	Detection Limit (LOD)	Reference
QD–MOF	High surface area, analyte enrichment	Multi-step synthesis	Complex food matrices	**0.000108 nM**	(Zhang et al., 2026)
QD–Polymer	Flexible, portable sensing	Polymer optimization	On-site food analysis	**400 nM**	(Li et al., 2026)
QD–Metal	Plasmonic signal amplification	Noble metal incorporation	Ultra-trace detection	**390 nM**	(Ge et al., 2026)
QD–MOF	Enzyme immobilization	MOF fabrication	Organophosphate screening	**6.57 nM**	(Xia et al., 2026)
QD–MOF	Catalytic signal amplification	Nanozyme synthesis	Agricultural samples	**0.05 μg/L**	(Su et al., 2026)
QD–Metal	FRET enhancement	Surface functionalization	Selective fluorescence sensing	**0.06 μg/L**	(Li et al., 2025)
QD–MOF	Aggregation-induced emission	Complex synthesis	Crop residue detection	**nM level** (keep as reported)	(Wahyudi et al., 2025)
QD–MOF	Enhanced ECL response	MOF/QD integration	Food & environmental monitoring	**0.14 μg/L**	(Tang et al., 2025)
QD–Polymer	Mechanical flexibility	Hydrogel preparation	Portable vegetable sensing	**0.0000447 nM**	(Gu et al., 2025)
QD–Metal	Improved electron transfer	AuNP electrode fabrication	Water monitoring	**0.15757 nM**	(Zhao et al., 2025)
QD–Hybrid	Efficient charge transfer	Composite synthesis	Photoelectrochemical sensing	**1.65 nM**	(Li et al., 2025)
QD–MOF	High surface area, analyte enrichment	Multi-step synthesis	Complex food matrices	**20 nM**	(Kumar and Rhim, 2025)

of 6.57 nM thiram in food and aquatic products. Graphene oxide/UCNP–QD hydrogel composites also achieved a limit of detection of 6.57 nM thiram in food and aquatic products and demonstrated excellent mechanical properties (1100% stretchability). Additionally, nanozyme–hydrogel systems enabled rapid detection with a detection limit of 157.57 pM in vegetables (Zhao et al., 2025). Overall, these platforms are well positioned for portable, field-deployable sensing in food and water environments. Recent engineering advancements show that the performance of sensors also depends on the morphology of the quantum dots as well as the engineering of the interfaces, chemistry of the surfaces, and design of the nanocomposites. All the methods discussed so far show that hybrid combination of various materials such as metal-organic frameworks, conductive polymers, metal nanoparticles, and derivatives of graphene yields better features in terms of sensitivity, electron transfer, and performance stability compared to the single-component technologies. At the same time, there still is a gap in research, as most of the studies only focus on small-scale feasibility studies without providing enough information on scalability, manufacturability, or reproducibility (Kumar and Rhim, 2025; Mani et al., 2025). While the analytical performance of hybrid nanocomposites is often better in laboratory settings, there is not always a direct link between the complexity of the structure and its applicability. The advantages of hybridization should therefore be considered based on the analytical problem in question and not automatically ruled as advantages based on the increased complexity of the architecture. Incorporation of MOF or magnetic nanomaterials is especially beneficial in complex food matrices as it can significantly minimize the matrix interference due to increased analyte enrichment, anti-fouling properties and mass transport. Likewise, conductive polymers and graphene materials are useful if there is a need for an improved charge transfer in electrochemical or photoelectrochemical sensing. However, in cases of relatively simple matrices like drinking water or laboratory-prepared aqueous samples, single-component QD sensors already provide detection limits that are comparable to or better than the regulatory limits, and an extra nanomaterial may only bring about a small improvement in analytical performance, while adding complexity to the fabrication process, production cost and batch-to-batch variability. Therefore, the design of hybrid QD nanosensors should be tailored to meet the application requirements such as matrix complexity, robustness, reproducibility, and manufacturability, not just emphasizing on the structures' sophistication (Li et al., 2021; Lim et al., 2015).

6.3. *Structure–activity relationships and design principles*

The results presented in this section suggest that the analytical performance of a quantum dot (QD) based pesticide nanosensor is not only defined by the material properties of the QD, but also by the interplay of the QD composition, the dimensions of the nanostructures, the surface chemistry of the QD and the recognition interface and sensor architecture. These structure–activity relationships will be helpful in rational design of next generation of sensing platforms (Pisanic et al., 2014; Yadav et al., 2023). Surface and composition of QDs have a significant effect on their optical and electrochemical properties. Semiconductor QDs could be used to create desirable and tunable optical properties for use in fluorescence-based sensing; carbon- and graphene-based QDs have the potential to provide attractive properties for surface functionalization and to minimize concerns with the use of heavy metal-containing materials. For this reason, the choice of material depends on the sensing mechanism, the analytes, the sample matrix and safety aspects (Safari, 2022). Surface functionalization is one of the most critical engineering strategies since it impacts analyte recognition, electron-transfer properties, colloidal stability and non-specific adsorption. Functional groups like carboxyl, amino, hydroxyl and thiol can enhance the number of binding sites and help to immobilize recognition elements. Likewise, the incorporation of heteroatoms such as N, S, P, and B can alter the electronic structure and surface defect states of QDs, which in turn can affect the catalytic activity and fluorescence of QDs [Rafi et al., 2025]. The other approach to controlling the QD sensing performance is hybrid nanocomposite engineering in which the key is understanding the complementary interactions between the QDs and the interface. The surface area can be increased by incorporating graphene derivatives, magnetic nanoparticles, metal nanoparticles, metal–organic frameworks (MOFs), or conductive polymers, and the electron transfer can be improved, analyte enrichment can be achieved, or signal amplification can be enhanced. However, the advantages of hybridization will be dependent on the composition and architecture of the hybrid interface and cannot be taken for granted. While in some instances, hybridization may enhance results of the analysis, too many structures may make fabrication more difficult, cause batch-to-batch variations, raise costs and make large-scale production and quality control more difficult (Safari, 2022). The recognition element also significantly affects the selectivity and stability of operation of the sensor. Aptamers can offer high molecular specificity along with relatively good chemical stability; molecularly imprinted polymers (MIPs) can offer artificial recognition sites with high robustness, which can be of great advantage under demanding sample conditions; enzymes offer high catalytic efficiency, but may be sensitive to environmental conditions; and antibodies can offer excellent molecular recognition, but may have higher production and storage requirements (Pisanic et al., 2014). Recent studies also reveal the benefit of using molecularly imprinted polymer (MIP) in conjunction with QD for increasing molecular selectivity in pesticide analysis. A study published in 2024, for instance, devised a

magnetic MIP nanocomposite that uses graphene quantum dots (GQDs) as fluorescent probes for the selective detection of the carbamate pesticide pirimicarb. The surface molecular imprinting, magnetic separation and GQD fluorescence enabled a multifunctional platform for selective recognition and analyte enrichment along with optical signal generation (Saadatidizaji et al., 2024). Recently, MIP-coated QDs were used for the trace detection of diflubenzuron in vegetable matrices, for which the silica-based MIP was employed (Feng et al., 2025), showing the potential of MIPs coated onto QDs for detection of pesticides in complex matrices such as vegetables. These studies are an example of an important design principle: that the optical transduction function can be performed by QDs and the MIP layer can enhance molecular recognition while minimizing nonspecific interactions. As the thickness or complexity of the imprinted layer are increased, however, there is also a possibility that the analyte diffusion could be impaired and the accessibility of the signal could be decreased. Therefore, optimization of the density of the imprinting sites, thickness of the polymer layer, QD surface chemistry and transport of the analytes is needed to reach the desired level of selectivity and sensitivity. Therefore, the selection of the recognition strategies must be based on the physicochemical characteristics of the pesticide to be recognized, the kind of matrix in which the pesticide is expected to occur and the operational conditions. In summary, for high-performance pesticide nanosensors, the following principles should be taken into account: (1) environment-friendly selection of the appropriate optical or electrochemical property of the QD; (2) control of surface chemistry to maximize target recognition, while minimizing the nonspecific interaction; (3) introduction of hybrid components only when they have a specific analytical function; (4) optimization of the recognition interface to achieve an appropriate balance between selectivity, stability, and accessibility; and (5) validation of the resulting sensor under realistic sample conditions. The principles of these are based on the idea that the performance of the sensor should be optimized by establishing a structure–property–performance relationship instead of choosing a single parameter such as the fluorescence intensity or the limit of detection (Yadav et al., 2023). In Table 8, the principle engineering approaches and their projected impacts on pesticide sensing using QD's are given.

7. Applications in food and water systems

This section of the article describes the applications of the quantum dot (QD)-based sensors for monitoring pesticides in both food and water. The main objective of this section is to evaluate how QD-based sensing platforms are performing in real analytical matrices with a specific focus on the pesticides being analyzed, the sensing mechanism employed, detection effectiveness, effects on the matrix, sample preparation, and practical use. To ensure that the review remains within the QD boundaries, only real examples of sensing platforms based on QDs are presented. Other examples of nanomaterials-based sensors are mentioned only when they are essential for purposes of contextualizing relevant points and explicitly stated that they are non-QD (Mahmoudi et al., Sep 2023).

7.1. QD-based detection of pesticides in food matrices

Food matrices pose a difficult problem for nanosensors based on QD, due to the interference caused by proteins, lipids, carbohydrates, pigments, salts, and fluorescent compounds. However, the adjustable properties of QDs, their high ratios between masses and volumes, and the possibility of modifying the surface of QDs are advantageous for the application of QDs for the detection of residues of toxic substances in fruits, vegetables, grains, beverages, and food products. Platforms based on QDs include optical, FRET, electrochemical, and photoelectrochemical measurements among which combinations with aptamers, enzymes, antibodies, and molecularly imprinted receptors are very common. It could be worth noting that it is important to focus on the performance of QDs in actual food matrices rather than in buffered solutions, concerning recovery, matrix effects, selectivity, stability, and sensitivity (Sahoo et al., 2017). The engineering principles discussed previously are examined here in representative food and water applications to assess their practical performance under different analytical conditions. The quantum dot (QD)-based nanosensors are also gaining a lot of interest as they possess tunable optical properties, high sensitivity and are potentially amenable to complex food sample like fruits and vegetables for the detection of pesticide residues in real food matrixes. Specifically, QDs can be used as fluorescent or electrochemiluminescent signal transducers, and can be combined with recognition elements such as acetylcholinesterase (AChE), aptamers, antibodies, and molecularly imprinted materials. Organophosphate pesticides (OPs) inhibit the activity of AChE and the biochemical reaction can be sensed by the optical or electrochemical properties of the QD component, in the case of an inhibition-based sensing mechanism. It is important to note that in this section, only AChE-based platforms with QDs are included as QD-based nanosensors, while platforms based only on MOFs, aerogels or other kinds of nanomaterials are not included in the term QD-based nanosensors (Su et al., 2026). Likewise, AChE-inhibition based QD biosensors have been shown to have a great potential for pesticide detection in food matrices. A biosensor based on a CdTe QD was designed for organophosphorus pesticides (OPs) detection in vegetable and fruit samples with detection limits of 1.05×10^{-11} M for paraoxon and 4.47×10^{-12} M for parathion and excellent reproducibility and accuracy for real samples (Zheng et al., Feb 15 2011). Lately, CDTe QD/AChE/choline oxidase fluorescence biosensor has been used to detect paraoxon, dichlorvos, malathion and triazophos with detection limits of 1.62×10^{-15}, 7.53×10^{-14}, 2.3×10^{-19}, and 1.06×10^{-11} M, respectively (Korram et al., 2020). The direct integration of QDs with enzyme-inhibition recognition was

Table 8
Representative structure–activity relationships illustrating how engineering strategies influence the structural characteristics, sensing performance, and rational design principles of quantum dot-based pesticide nanosensors.

Engineering strategy	Structural effect	Performance improvement	Design principle	Ref.
N- or heteroatom doping	Introduces defect states and modifies the electronic structure	Enhanced fluorescence, charge separation, and/or catalytic activity	Control defect density and electronic structure to optimize signal generation	(Cui et al., Dec 16 2021)
Graphene hybridization	Provides conductive pathways and increases accessible interfacial area	Improved electron transfer, charge transport, and electrochemical signal response	Optimize QD–graphene interfacial contact while preserving QD optical properties	(Rasheed et al., 2024)
MXene/MOF integration	Provides conductive or porous interfaces with high accessible surface area	Enhanced charge transport, analyte enrichment, and signal amplification	Match pore structure and interfacial chemistry to the target analyte and sensing mechanism	(Ali et al., 2024)
Aptamer functionalization	Provides specific molecular recognition sites on the QD surface	Improved selectivity and reduced interference	Match aptamer affinity and surface density to the target pesticide	(Rabiee and Rabiee, 2024)
Surface passivation/ functionalization	Reduces surface traps and controls surface chemistry	Enhanced fluorescence efficiency, photostability, colloidal stability, and operational stability	Minimize non-radiative recombination and nonspecific adsorption while maintaining analyte accessibility	(Zhang et al., 2022)

demonstrated by the fluorescence response, which was correlated to the inhibition of AChE by OPs. A carbon quantum dot (CQD)-based fluorometric sensor was also prepared for screening AChE inhibitors and malathion and chlorpyrifos were detected with detection limits of 1.70 ng/mL and 1.50 ng/mL, respectively (Mahmoudi et al., Sep 2023). Moreover, CQDs have been used in conjunction with AuNPs as a fluorescence probe for monitoring the inhibition and reactivation of AChE, which is the first example of the use of the hybrid architectures of QD–metal nanoparticle for pesticide sensing. These studies can be directly used to support the use of QDs as signal transducers in AChE-inhibition based pesticide biosensors instead of just as auxiliary nanomaterials. In addition to pesticides, which are typically based on organophosphorus, another class of pesticides, such as carbamates, pyrethroids and neonicotinoids, have been explored for use with QD-based nanosensors. Selective detection of pesticides is possible with fluorescence-based QD platforms by exploiting the following mechanisms which are capable of modulating the signal: fluorescence quenching, fluorescence recovery, Förster resonance energy transfer (FRET), inner filter effect (IFE), etc. Furthermore, the QDs can be combined with other materials like MOFs, AuNPs, AgNPs, polymers and magnetic nanomaterials to develop hybrid sensing architectures. In these systems, the complementary material serves to fulfill functions including adsorption, catalysis, plasmonic enhancement, charge transfer and/or signal amplification, while the QD is a component of the signal itself. Hence, any platform with a hybrid sensor system should be considered a QD based platform, only if the QD is a vital part of the sensing system.

Real food matrices should be used as well as standard (solutions) matrices to evaluate the practical performance of QD-based nanosensors. Proteins, lipids, carbohydrates, pigments, salts and naturally fluorescent compounds in the matrix may impair the recognition of analytes and signal generation. Therefore, recovery, precision, selectivity, matrix effects, operational stability and comparison with applicable maximum residue limits (MRLs) are significant parameters to consider in assessing the practical utility. Real fruit and vegetable studies have shown that a sensing platform based on QDs can achieve rapid and sensitive detection of pesticides while maintaining good analytical performance in the complex matrix (Korram et al., 2019). Reported detection limits however should be viewed in conjunction with the regulatory requirements as well as the sample preparation method, and not solely as a measure of superior practical performance. Table 9 shows representative nanosensor systems based on QD for pesticide detection in food systems.

7.2. QD-based detection of pesticides in water and environmental samples

An important area of application for QD-based pesticide nanosensors is in water and environmental matrices because of the capacity of pesticide residues to stay and move from agricultural zones into water bodies, underground waters and other environmental areas. QD-based systems have the potential for rapid and effective detection of pesticide residues at trace levels using fluorescence, electrochemical, photoelectrochemical, and FRET technologies. Compared to food matrices, water samples usually include less protein and lipid content but may contain natural organic matter, inorganic ions, suspended solids and other pollutants that may influence sensing performance. Thus, the new-generation QD-based nanosensors should be evaluated regarding efficiency, selectivity, recovery, operational stability, and performance in real-life environmental samples rather than in traditional buffer solutions only (Zhou et al., 2018). QD-based nanosensors are among the most powerful tools for detecting pesticide residues in diverse water systems because they are ultra-sensitive, rapid, and capable of real-time monitoring. Pesticide contamination of drinking water is a serious concern worldwide; compounds such as chlorpyrifos have been detected in several countries at concentrations of several μg/L, posing substantial risks to human health (Chaudhary et al., 2025). The tunable optical properties, high surface-to-volume ratio, and ease of rapid and portable detection of nanosensors make them promising tools for measuring pesticide residues in water and other environmental matrices. For instance, carbon quantum dot (CQD) modified photoelectrochemical sensors were used to detect triazophos with a very low detection limit of 0.03 nM in water system (Zeng et al., 2024). Likewise, the ability of CdTe QDs to form electrochemiluminescent aptasensors was exploited for femtogram-level detection of organophosphorus pesticides like diazinon, which will be useful in detecting pesticides at trace level in water (Li et al., 2025). Portable and relatively low cost approaches to routine environmental monitoring can also be offered using the carbon dot-based fluorescence sensors (Rohit et al., 2023). These may lower the

Table 9
Representative nanosensor-based detection systems for pesticide residues in food matrices, highlighting sensor types, sample applications, and analytical sensitivity.

System Type	Food / Vegetable Sample	Detection Limit (LOD)	Reference
DNA-based electrochemical biosensor	Apple, Garlic	**~0.005 nM**	(Elshafey et al., 2026)
Graphene QD electrochemical biosensor	Apple, Pear	**10 nM**	(Pengsook et al., 2026)
Lateral flow immunoassay (AIE nanoparticles)	Cowpea, Celery, Chives, Orange, Pear	**0.012–0.032 μg/L**	(Su et al., 2026)
Aptamer lateral flow biosensor	Vegetables	**12.61 nM**	(Fang et al., 2026)
Hydrogel UCNP/GO aptasensor	Tea (cereal-type beverage)	**0.108 μg/L**	(Zhu et al., 2026)
Fluorescent aptasensor (MWCNT/AuNP)	Bell pepper (vegetable)	**0.0028 nM**	(Gholami et al., 2025)
SERS magnetic nanosensor + ML	Edible fungi (food category)	**5.21–11.6 μg/kg**	(Liu et al., 2026)
SERS portable substrate	General food (field testing)	**100 μg/L**	(Arora et al., 2026)
Fluorescent hydrogel microneedle (DNA-AgNPs)	Fish/meat surface	**6.57 nM**	(Xia et al., 2026)
Carbon dot optical nanosensors	Fruits, vegetables (general)	**Ultra-low (varies by system)**	(Li et al., 2025)
GQDs–AgNP dual-mode nanoprobe	Carrot	**0.017 μg/L**	(Li et al., 2020)
N-doped carbon dots sensor	Cucumber, Rice	**150 nM (0.017 mg/L Hg = 17 μg/L)**	(Zhang et al., 2025)
Rhodamine-CQDs fluorescence sensor	Environmental/ Food	**19.25 nM**	(Li et al., 2026)
CQDs electrochemical aptasensor	Potato	**0.000834 nM**	(Himanshu et al., 2024)
N-doped CQDs fluorescent sensor	Vegetables	**3.5 μg/L**	(Patel et al., 2023)
CQDs-based SERS aptasensor	Apple peel	**1.20 ng/cm²**	(Wei et al., 2024)
CQDs multienzyme electrochemical sensor	Mango	**2.01 nM**	(Ji et al., 2024)
CdTe QDs microfluidic paper sensor	Bean sprouts	**90 nM**	Zhang et al., 2019
CQDs dual-mode fluorescence sensor	Environmental/ Food	**0.21 μg/L; 0.46 μg/L**	(Gupta et al., 2019)
Perovskite QDs ($CsPbBr_3$) sensor	Vegetables, Soil	**18.8 μg/L**	(Huang et al., Nov 14 2018)
Core–shell QDs fluorescence sensor	Medicinal plants	**<50 nM**	(Wei et al., 2018)
Carbon dots fluorescence probe	Vegetables	**3 μg/L**	(Lin et al., 2018)
N-GQDs aptamer fluorescence sensor	Environmental/ Food	**0.041 nM**	(Zhang et al., 2017)

necessity for complicated instrumentation and tons of sample preparation, enabling the decentralisation of water quality measurements and possibly even in the field. Surface and ground water contamination with pesticides is often related to agricultural activities and surface run-off and some organophosphorus pesticides can be persistent, enhancing their potential to be transported and accumulate in the environment. Hence, the use of QD-based fluorescence and electrochemical platforms have been explored for pesticide detection in river water and other environmental matrices. A case in point is the use of CQD-based fluorescence nanosensors coupled with metal–organic frameworks (MOFs) for the detection of glyphosate in river water where the detection limit was 0.07 μM with a satisfactory analysis performance was reported (Hui et al., 2025). In the hybrid architecture, the CQDs are used as the QD part and the MOF is used as an auxiliary material which can provide adsorption and enrichment sites. Likewise, pesticide detection in water samples such as malathion using graphene quantum dot (GQD)-based hybrid systems has been explored, and the detection limits are claimed to be in the range of ng/mL (Dan et al., 2021). These examples illustrate how QDs can be combined with other complementary nanomaterials to enhance the enrichment of analytes, the generation of signals, and the overall analytical performance in complex aqueous samples. Pesticides can be transported into surface water, ground water, wastewater and agricultural drainage via runoff, irrigation and other routes. Nanosensors based on QD are especially attractive for environmental monitoring for their ability to combine their optical and electrochemical response with portable instrumentation and simplified analytical procedures. However, recent biosensing applications using CQD have also shown the potential for detecting pesticides in contaminated wastewater and agricultural run-off with rapid response and decentralized environmental monitoring (Raqba et al., 2025). However, before applying in practice, matrix effects, recovery, selectivity, operational stability and long-term performance must be evaluated in the real environmental samples. Thus, reported detection limits should be viewed in conjunction with validation in real matrices and, if available, relevant environmental guideline and/or regulation values. The representative nanosensors-based platform for pesticide detection in water and environmental samples is summarized in Table 10.

7.3. Multi-residue detection platforms

Multiplex QD-based nanosensors represent a major advance in pesticide detection by enabling multi-residue analysis within a single platform. These systems exploit the unique optical properties of QDs, including size-dependent emission and high photostability, to support detection of multiple analytes using distinguishable fluorescence signals. Recent studies indicate that dual- and multi-signal systems can increase analytical throughput and reduce analysis time relative to traditional single-target assays.

For example, electrochemiluminescent (ECL) nanosensors integrating CRISPR/Cas12a with AgNP-modified MOFs simultaneously detected malathion and phorate, with ultra-low limits of detection of 0.108 pM and 1.01 pM, respectively, in cabbage and lettuce samples, and recoveries of 95.7–106.4% (Vadia et al., 2025). Similarly, microfluidic paper-based analytical devices (μPADs) incorporating upconversion nanoparticles (UCNPs) enabled multiplex detection of glyphosate, malathion, and acetamiprid, with detection limits of 0.133–0.232 ng/mL that were consistent with HPLC validation (Zhu et al., 2025). A ratiometric CQD multiplex system operating via fluorescence enabled simultaneous detection of pesticides and co-contaminants, with limits of detection of 2.71×10^{-3} μM and 1.86×10^{-3} μM; the multimode output improved signal reliability (Li et al., 2026). Notably, dual-color QD immunochromatographic assays for pesticide residues exhibited a detection limit of 0.611 pg/mL and a time to result of approximately 15 min (Chen et al., 2025). FRET-based dual-target systems and nanozyme-based sensor arrays can also detect chemically distinct analytes without cross-interference, including at nanomolar concentrations (Aslam, 2026).

Table 10
Nanosensor-based detection systems for pesticide residues in water samples, highlighting sensor types, detection limits, and analytical performance across environmental matrices.

System Type	Water Sample	Detection Limit (LOD + Pesticide)	Reference
Cu–N doped CQDs fluorescence sensor	Water	**0.43 μg/L** (Malathion)	(Salman, 2025)
N-doped carbon dots fluorescence sensor	Water	17 **μg/L** (Thiophanate-methyl)	(Zhang et al., 2025)
Carbon dots nanozyme sensor	Water	490 nM (Hymexazol)	(Zhang et al., 2026)
Carbon dots smartphone sensor	Water	2870 nM (Glyphosate)	(Lei et al., 2025)
F-CQDs dual-emission fluorescence probe	Environmental water	8.6 nM (Chlorothalonil)	(Li et al., 2025)
Cu NCs fluorescent sensor array	Tap water	~7.1 μg/L (Multiple pesticides)	(Chen et al., 2025)
CdS QDs PEC biosensor	Water	**0.05 μg/L** (Chlorpyrifos)	(Huang et al., 2025)
CQDs PEC sensor	Water	0.03 nM (Triazophos)	(Zeng et al., 2024)
GQDs-based electrochemical sensor	Water	0.046 ng/L (Parathion)	(Mehta et al., 2017)
CQDs FRET fluorescence sensor	Water	0.05 μg/L (Paraoxon)	(Wu et al., 2017)
N-doped GQDs fluorescence sensor	Environmental water	1.2 μg/L (Atrazine)	(Wang et al., 2019)
Carbon dots fluorescence nanosensor	Water	0.25 μg/L (Diazinon); 2 μg/L (Glyphosate)	(Ashrafi Tafreshi et al., 2020)
VS_2 quantum dots electrochemical aptasensor	Water	0.000002 nM (Diazinon)	(Wang et al., 2019)
Green carbon dots fluorescence sensor	Water	0.5 μg/L (Amicarbazone)	(Ashrafi Tafreshi et al., 2020)
RS-CDs ratiometric fluorescence probe	Tap, river & irrigation water	2300 nM (Chlorpyrifos)	(El-Shaheny et al., 2025)
N-CQDs@Fe_3O_4 electrochemical nanosensor	Water	1.2 nM (o-Nitroaniline pesticide intermediate)	(Ragu et al., 2023)

7.4. Portable and on-site detection systems

Paper-based nanosensors have emerged as low-cost, disposable, and user-friendly platforms for on-site pesticide detection. These devices integrate QDs, carbon dots, or nanozymes into lateral flow assays (LFAs), microfluidic paper formats, and hydrogel strips, enabling rapid visual or fluorescence readouts. Recent studies indicate that paper-based systems can achieve sensitivities comparable to laboratory-based approaches. For example, a two-color QD-based immunochromatographic strip achieved femtogram-level detection (0.611 pg/mL), with a response time of <15 min and recovery of 85–105%. Similarly, aptamer biosensors operating in lateral-flow mode reached an LOD of 12.61 nM for isofenphos-methyl in food, supporting practical implementation in food-safety monitoring (Fang et al., 2026). QD- and UCNP-based paper microfluidic tools have also enabled simultaneous determination of multiple pesticides, with a response time of approximately 25 min and sub-ng/mL sensitivity (Zhu et al., 2025). Smartphone-enabled nanosensors represent an emerging frontier in portable detection, combining

QD-based sensing with digital imaging, artificial intelligence (AI), and cloud-based analysis to support real-time, quantitative field measurements. For instance, CQD-based ratiometric sensors integrated with smartphones can enable quantitative analysis via RGB signal extraction, with a reported glyphosate detection limit of 2.87 μM (Lei et al., 2025). Nanophotonic sensors combined with deep-learning algorithms have shown high predictive accuracy ($R^2 = 0.987$) and rapid measurement times (approximately 5 s) via mobile applications that enable real-time monitoring (Molina-González et al., 2026). In addition, Smartphone imaging captures fluorescence emitted by quantum dots and converts it into quantitative pesticide concentrations through image-processing algorithms (Zou et al., 2025). Overall, the use of smartphones in conjunction with these types of sensors provides advantages in terms of portability, data processing, and user access to information, thereby providing a means of supporting decentralised real-time food safety monitoring. Schematic representation of (a) multiplex-based CQD nano sensors for simultaneous, multiple pesticide detection; and (b) mobile phone-enabled portable point-of-service detection system that incorporates either paper-based sensor or CQD-based sensors. Fig. 9 illustrates portable quantum dot-based platforms, including lateral flow assays and smartphone-assisted systems, for rapid on-site pesticide detection. While many sensing platforms based on QD have shown excellent analytical performance in laboratory tests, there are relatively few examples of platforms that have advanced to routine field deployment. While there are many published systems for validation of these systems, only a few have been validated using naturally contaminated food and environmental samples, respectively, under controlled experimental conditions. In addition, complex sample matrices, environmental conditions and long-term operation stability are often a problem with sensor performance. Although there are various platforms for portable sensing that have been integrated with smartphones and paper-based platforms, as well as microfluidic platforms, there are still a

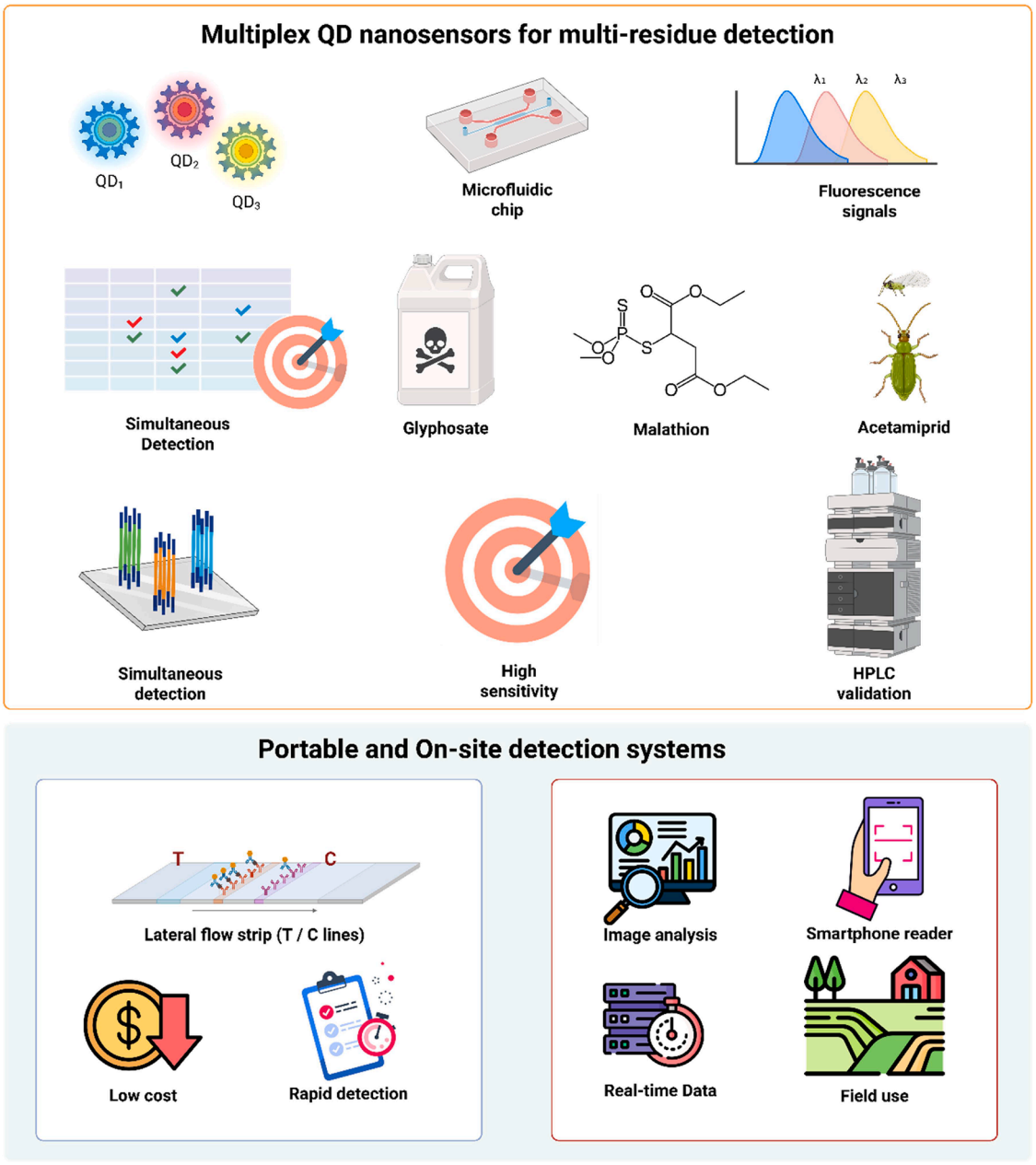


Fig. 9. Portable and on-site detection systems for pesticide monitoring, highlighting nanosensor-based platforms, lateral flow assays, and smartphone-assisted analysis for rapid, low-cost, and real-time field applications.

need for standardized validation procedures, regulatory clearance and large-scale manufacturing before these platforms can be widely commercialized.

7.5. Multiplex detection and array-based quantum dot sensing

In the future, monitoring of food safety is likely to rely on multiplex sensing principles in which quantum dots (QD) are part of the sensor, thanks to the widespread presence of several pesticide residues, veterinary drugs, mycotoxins, heavy metals and other contaminants in the same food product. Conventional single-analyte sensors are unable to identify and quantify multiple target compounds in a single analytical measurement, which increase analysis time, reagent usage, and operational costs, and decreases analytical throughput. Multiplex sensing allows simultaneous identification and quantification of multiple target compounds in a single analytical measurement, increasing analytical throughput, reducing analysis time, reagent usage, and operational costs. The remarkable optical properties of QDs are in part their narrow bandwidths, broad excitation spectra, high fluorescence quantum yields, and excellent photostability, rendering them particularly well suited for multiplex fluorescence sensing. The different QDs can be designed to release unique fluorescence signals in response to a single excitation source, such that a variety of pesticides could be encoded using spectrally separated emission peaks, with only a small overlap in the spectrum. Such spectral encoding greatly increases the efficiency of the analysis, retaining high sensitivity and selectivity (Shen et al., 2022; Yuan et al., 2023). In recent advances, fluorescent sensor arrays, aptamer-functionalized QDs, molecularly imprinted polymers (MIPs), and hybrid nanocomposite platforms that were able to resolve structurally related pesticides by multidimensional fluorescence response patterns have also been built. When used in conjunction with chemometric analysis, principal component analysis (PCA), linear discriminant analysis (LDA) and machine learning algorithms, these array-based sensing systems can accurately classify and quantify multiple analytes, even when they are present in complex food matrices (Banicod et al., Oct 12 2025; Chen et al., 2025). However, a number of issues remain that hinder broad application. When many analytes are measured at the same time, there may be a reduction of quantitative accuracy due to a number of sources of error, including spectral overlap of fluorophores, fluorescence cross-talk, signal calibration, variable binding affinities, and matrix-dependent interference. In addition, before the routine use of multiplex platforms becomes a reality, reproducible methods for fabricating multi-coloured QDs, standard calibration procedures, and validation with real food samples should be developed (Cedrún-Morales et al., Apr 16 2026; Chen et al., 2025). The development of multiplex QD sensor, portability of the fluorescence reader, smartphone-based imaging, lab-on-a-chip microfluidic device and artificial intelligence assisted spectral decoding is expected to enable rapid, on-site, high--throughput, and onsite monitoring of pesticide residues and other food contaminants. The integrated platforms will become more and more relevant for precision food safety monitoring and environmental surveillance (Banicod et al., Oct 12 2025; Cedrún-Morales et al., Apr 16 2026). The conceptual framework of multiplex QD-based sensing is shown in Fig. 10, which illustrates the combination of multicolour quantum dots, spectral encoding, receptor-array recognition, chemometric and AI-assisted data analysis, and simultaneous multi-residue detection for quick and sensitive food safety monitoring.

Artificial intelligence (AI) is predicted to be a game-changer in the development of next-generation QD-based pesticide nanosensors, not just in multiplex spectral decoding, but also in sensor design, analytical optimization, and intelligent decision-making (Hassan et al., 2025; Zhou et al., 2024). To reduce experimental trial-and-error and improve synthesis parameters, surface modification, and the response of the fluorescent signal, diverse machine learning algorithms have been applied in optimizing synthesis parameters for QD, such as artificial neural networks (ANN), random forest (RF), random forest classifiers, convolutional neural networks (CNN), and deep learning approaches (Zhou et al., 2024). Moreover, AI can help in the automatic interpretation of complex fluorescence fingerprints, the compensation for matrix interference, prediction of sensor performance, and the detection of subtle analytical patterns that are difficult to distinguish by using a conventional calibration method (Yi et al., 2024). Additionally, the combination of AI and imaging technology on mobile devices, cloud computing, Internet of Things (IoT) networks, and edge computing facilitates live data analysis, remote surveillance, automated quality control, and quick decision-making for food safety management (Hassan et al., 2025; Yi et al., 2024). Even with these benefits, there are several challenges that must be addressed to implement the technology on a broader scale,

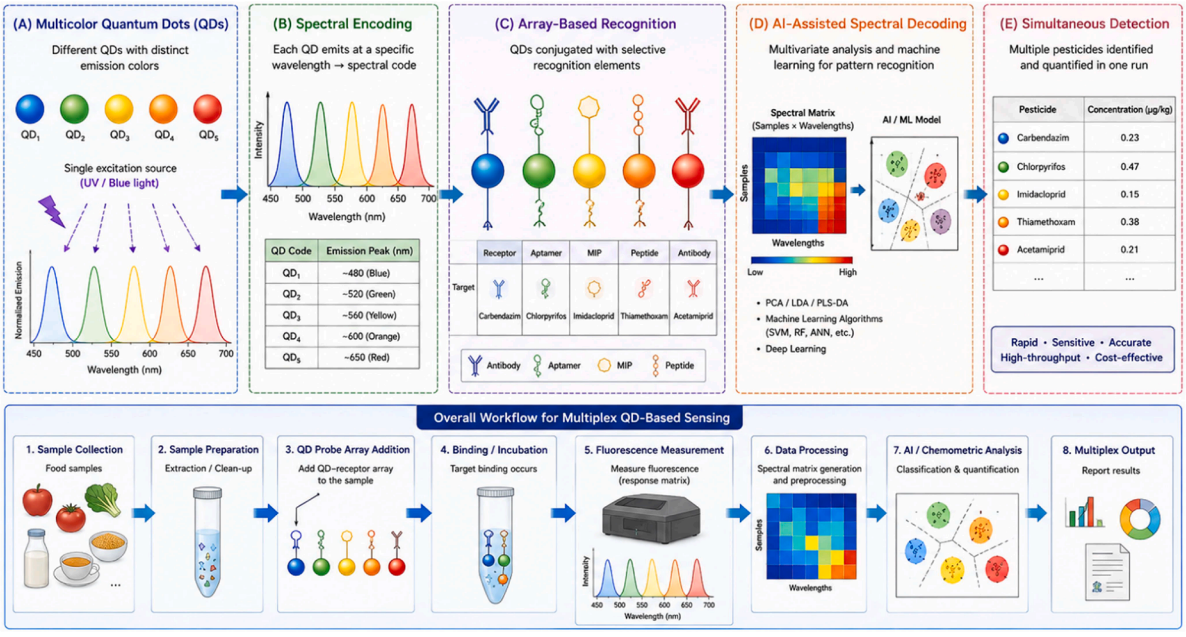


Fig. 10. Conceptual illustration of multiplex quantum dot-based sensing showing multicolor QDs, spectral encoding, array-based recognition, AI-assisted spectral decoding, and simultaneous detection of multiple pesticides in food samples.

including the need for standardized datasets, the validation of the models, and the need for explainability of the AI models and their use in routine food and environmental monitoring that must be accepted by regulatory bodies (Hassan et al., 2025). Hence, the combination of advanced nanomaterials with AI is anticipated to be a key cornerstone in the realization of the next-generation of smart, self-optimizing and completely self-contained QD-based sensing platforms. Table 11 summarizes the major AI techniques and their applications in enhancing the performance of QD-based pesticide nanosensors for food safety monitoring.

Despite many studies underlining that even more lower detection limits are being reached, sensitivity should not only be regarded as a sufficient parameter characterizing the performance of the sensor. As far as practical pesticide analysis is concerned, the ability to quantify the target substance at the concentration close to the MRL would be more beneficial than to find the target substance at femtomolar levels. For this reason, other parameters such as recovery, selectivity, reproducibility, tolerance to matrix effects, time characteristics, etc. should also be taken into account while assessing the sensor performance.

8. Performance evaluation and comparison

8.1. Sensitivity and detection limits

Nanosensors utilizing quantum dots (QDs) exhibit exceptional performance, with detection capabilities far exceeding those of less sensitive analytical techniques. This high performance is attributed to the strong fluorescence emission of QDs, their large surface-area-to-volume ratio, and multiple signal-enhancement mechanisms, including fluorescence resonance energy transfer (FRET) and electrochemical luminescence. For example, detection limits achieved using a combination of carbon quantum dots (CQDs) and gold nanoparticles (AuNPs) for organophosphate pesticide detection in solution (in both water and apple juice) have been reported as 0.05–0.13 nM for paraoxon, malathion, and carbaryl, demonstrating the ultra-low detection limits obtainable with CQD–AuNP systems. In the same context, (Wang et al., 2025) reported that NiFe-layered double hydroxide (LDH)/MXene biosensors achieved a limit of detection (LOD) of 1.459×10^{-11} M for dimethoate, indicating that femtomolar-level sensitivities can be achieved in complex food matrices (Yi et al., 2024) also reported that dichlorvos detection in cabbage and pakchoi using a carbon--dot–nanozyme system yielded an LOD of 7.6 nM. Furthermore, the integration of a smartphone enabled the detection of paraoxon-methyl with an LOD of 0.304 ppt, highlighting the ability of portable platforms to reach extremely low detection limits (i.e., parts per trillion) (Maanaki et al., 2023).

8.2. Selectivity in complex matrices

Selectivity is critical in matrices containing multiple potentially interfering components (such as proteins, pigments, and organic materials) that may affect detection performance. QD-based nanosensors exhibit high selectivity due to the use of biorecognition elements e.g., enzymes, aptamers, and antibodies to drive analyte-specific binding. Aptamer-modified CQDs showed very high specificity for acetamiprid, with minimal effects from other pesticides (Wang et al., 2025). Matrix effects are particularly evident in food systems compared with water. Many studies confirm that nanosensors can still provide good performance in vegetable matrices, with recoveries of 76.8–105.9% and reliable quantification despite the complexity of the vegetable matrix (Sun et al., 2013). Immunosensors also demonstrated strong selectivity for imidacloprid, with little or no cross-reactivity, while maintaining good performance in both watermelon and water samples (Pérez-Fernández et al., 2020).

8.3. Response time and portability

QDs-based nanosensors can achieve rapid detection times in minutes, enabling real-time monitoring. For example, OPAA–CQD thin-film biosensors have been shown to detect target analytes in under five minutes, indicating very fast response kinetics. Similarly, microfluidic paper-based devices have enabled detection in approximately 25 minutes, offering a combination of rapid analysis and multiplexer capabilities (Zhu et al., 2025). In addition, portable platforms enhance the usability of these technologies. Smartphone-integrated systems enable data acquisition and analysis in real time and have achieved precise detection (RSD $< 5\%$) and recovery (approximately 98.3%) (Maanaki et al., 2023). Finally, paper-based sensors provide low-cost, single-use, field-deployable technologies that enable on-site detection without reliance on complicated instrumentation (Zhang et al., 2025). A comparison between QD-based nanosensors and conventional analytical techniques is presented in Table 12**.** Overall, QD-based nanosensors can achieve low detection limits, high selectivity, and rapid response for pesticide analysis. Nevertheless, analytical sensitivity alone is insufficient to establish practical performance. Reproducibility, storage stability, matrix tolerance, fabrication cost, portability, and regulatory compliance must also be considered when assessing real-world applicability. Future research should therefore emphasize standardized performance testing based on internationally accepted analytical procedures, together with cost-effective fabrication strategies that support translation from laboratory prototypes to practical pesticide-monitoring systems.

8.4. Design implications and critical evaluation of performance differences

The analytical performance discussed in this section shows that the differences in analytical performance between the various analytical sensing platforms are not due to the choice of quantum dot, but instead are due to fundamental differences in the materials, in the nature of the signal transduction, and in the architecture of the sensor. Thus, it is important to consider the performance in light of the sensing mechanisms and engineering strategies discussed herein (Yang et al., 2023; Yu and Schanze, Nov 22 2023). The quantum dots with high fluorescence

Table 11
Applications of artificial intelligence (AI) in quantum dot (QD)-based pesticide nanosensors for sensor optimization, spectral decoding, pattern recognition, portable sensing, and real-time food safety monitoring.

AI Application	AI Technique	Function	Benefit	Verified References
Sensor optimization	ANN, Random Forest	Optimize QD synthesis and sensing conditions	Improved sensitivity and reproducibility	(Hassan et al., 2025; Zhou et al., 2024)
Spectral decoding	CNN, Deep Learning	Analyze multicolor fluorescence spectra	Multiplex detection and automated fluorescence interpretation	(Awlqadr et al., Mar 1 2026; Zhou et al., 2024)
Pattern recognition	PCA, LDA, SVM	Classify pesticide fluorescence fingerprints	Improved selectivity and analytical accuracy	(Hassan et al., 2025; Zhou et al., 2024)
Portable sensing	Computer vision	Smartphone image analysis	Rapid on-site food safety monitoring	(Upadhyay et al., Aug 1 2024)
Smart monitoring	AI + IoT	Real-time data transmission, cloud analytics, and prediction	Continuous food safety surveillance	(Hassan et al., 2025)

Table 12
Comparative analysis of quantum dot (QD)-based nanosensors and conventional analytical techniques (GC–MS, LC–MS, and HPLC) for pesticide detection, highlighting differences in sensitivity, analysis time, cost, and practical applicability.

Parameter	QD-Based Nanosensors	GC–MS / LC–MS / HPLC (Conventional Techniques)	Supporting References
Sensitivity (LOD)	Ultra-low (fM–nM, ppt levels); e.g., 0.304 ppt (paraoxon), 10^{-11} M (dimethoate)	Very high (ng/mL–μg/L range); regulatory standard compliance	(Maanaki et al., 2023; Wang et al., 2025)
Selectivity	High with aptamers, enzymes, antibodies; potential cross-interference in complex matrices	Very high due to chromatographic separation coupled with sensitive detection	(Pérez-Fernández et al., 2020)
Analysis Time	Rapid (seconds–minutes; typically 5–25 min)	Long (30 min to several hours including preparation)	(Kaur et al., 2026; Zou et al., 2025)
Sample Preparation	Minimal or none (direct or simple extraction)	Complex (extraction, purification, derivatization required)	(Kaur et al., 2026; Sun et al., 2013)
Portability	Highly portable (paper-based, smartphone-integrated systems)	Non-portable (lab-based instrumentation required)	(Maanaki et al., 2023)
Cost	Low-cost materials and operation	High cost (equipment, maintenance, reagents)	(Kaur et al., 2026)
Operation Complexity	Simple; suitable for non-specialists	Requires trained personnel and technical expertise	
Real-Time Detection	Yes (on-site, real-time monitoring possible)	No (offline laboratory analysis)	(Maanaki et al., 2023)
Accuracy & Reliability	High; validated with strong correlation to HPLC/GC results	Gold standard with highest accuracy and reproducibility	(Dong et al., 2024; Yang et al., 2024)
Multiplex Detection	Possible (multi-residue detection with QDs, microfluidics)	Limited; requires sequential or complex methods	(Zhu et al., 2025)
Practical Role	Rapid screening tool for field analysis	Confirmatory method for regulatory and legal validation	(Zhang et al., 2025)

quantum yields, narrow emission spectra and excellent photostability, generally have the lowest limits of detection in fluorescence-based nanosensors. In addition, there are mechanisms of fluorescence quenching and enhancement that can provide highly sensitive amplification of the signals via Förster resonance energy transfer (FRET), electron transfer or inner filter effects (Thévenot et al., 2001; Yu and Schanze, Nov 22 2023). However, in complex food and environmental samples, where there may be matrix interference, light scattering and background autofluorescence, it is often difficult to achieve analytical reliability under real-world conditions (Thévenot et al., 2001). Electrochemical sensors often possess more desirable properties of portability, fast response and miniaturization in analytical devices. The high performance is attributed to the efficient electron transfer at conductive interfaces especially when hybrid nanocomposites are made with graphene, MXenes, conductive polymers, and/or metal nanoparticles (Bakranov et al., 2026; Thakur et al., 2024). However, electrochemical systems can become affected by electrode fouling, surface degradation and changes in electrochemical background signals over time (Bakranov et al., 2026). The output of the photoelectrochemical (PEC) sensing is generated by both the optical excitation and the electrochemical signal; the process of reading out the output signal of PEC sensing is lower in background noise and higher in signal to noise ratio than for conventional electrochemical sensing. These characteristics can lead to very high analytical sensitivity, but in the process of fabrication, more sophisticated materials are typically needed for photoactive functionality and more complex sensor architecture, which restricts the large-scale implementation of PEC devices (Bakranov et al., 2026; Thakur et al., 2024).

Excellent molecular selectivity is observed with FRET-based sensing platforms since signal generation relies on very specific donor–acceptor interactions over nanometer-scale distances. Therefore, these systems are ideal for multiplex detection and molecular recognition. Their performance is however highly sensitive to the spatial control between fluorophores and recognition elements, leading to the relatively more complex fabrication of sensors (Thévenot et al., 2001; Yu and Schanze, Nov 22 2023). A comparison of the reported studies also shows that the analytical enhancement obtained from the hybrid nanocomposite engineering can provide greater analytical enhancement obtained from modifying individual QDs. The introduction of graphene derivatives, MXenes, metal nanoparticles, metal-organic frameworks (MOFs) or conductive polymers boosts electron–hole separation, increases the number of accessible active sites, prevents the recombination of electrons and holes, and amplifies signals. Such synergic effects are the reason why hybrid QD systems often yield superior sensitivity, selectivity and operational stability compared to pristine QDs (Bakranov et al., 2026; Thakur et al., 2024).

In general, there is no one 'best' sensing strategy. Instead, the platform that is best suited to the application is chosen. The fluorescence-based systems are still very appropriate for ultra-trace analysis in the laboratory, the electrochemical sensors are beneficial for portable and on-site monitoring, PEC sensors are superior for environmental monitoring, and FRET-based systems are very suitable for multiplex detection. Thus, future development of sensors should emphasize the synergy of complementary sensing mechanisms and optimized material engineering for improved balanced sensor sensitivity, selectivity, robustness, and practical application (Bakranov et al., 2026; Thakur et al., 2024; Thévenot et al., 2001; Yang et al., 2023; Yu and Schanze, Nov 22 2023). The strengths and limitations of the major QD-based sensing strategies are highlighted, along with design implications, in Table 13, which summarizes the strengths and limitations, and key considerations for the analytical performance and applications of each strategy. In terms of material, there are also significant material trade-offs that need to be taken into account in addition to the sensing mechanism, such as the choice of the composition of the QDs. The optical properties, as well as the high fluorescence efficiency and favorable electronic properties of heavy-metal based QDs, especially Cd-based QDs, can facilitate highly sensitive fluorescent, FRET and electrochemiluminescence detection. They are, however, potentially toxic; may release metal ions; may persist in the environment; and have regulatory issues, which make them inappropriate for use in food and environmental samples. In contrast, carbon quantum dots (CQDs) and graphene quantum dots (GQDs) are typically more appealing with regard to environmental friendliness and functionalization of the surface and offer a large number of surface groups to attach recognition elements. However, they can have highly variable optical and electronic properties depending upon the composition of the precursor, the synthesis conditions, surface defects, particle size, and functionalization which could create batch-to-batch variability and differences in analytical performance. Therefore, carbon-based QDs cannot be considered as a superior material over the semiconductor QDs, and the selection of the material should depend on the sensitivity, recognition mechanism, matrix, stability, safety, reproducibility, and application. Specific analytical functions can be further enhanced by hybridization with MOFs, graphene derivatives, conductive polymers, magnetic materials or metal nanoparticles, but this may bring extra complexity in the fabrication, scaling up, cost and quality control (Dua et al., 2023; Wang and Hu, 2014).

Table 13
Critical comparison of major quantum dot (QD)-based sensing strategies, highlighting their performance advantages, principal limitations, engineering implications, and representative references.

Sensing strategy	Why it performs well	Main limitation	Design implication	Representative references
Fluorescence	High quantum yield, strong signal amplification	Matrix autofluorescence	Improve surface passivation and anti-fouling coatings	(Algar et al., 2019; Qureshi et al., 2023)
Electrochemical	Fast electron transfer, conductive interfaces	Electrode fouling	Use graphene, MXenes, and conductive polymers	(Qureshi, Shaikh and Niazi, Apr 11 2023; Zhao et al., Nov 2024)
Photoelectrochemical (PEC)	Low background current, efficient charge separation	Complex fabrication	Develop stable, low-cost photoactive materials	(Lu et al., 2024; Monsalve et al., 2024)
FRET	Distance-dependent energy transfer, high specificity	Difficult donor–acceptor alignment	Optimize probe architecture and linker chemistry	(Algar et al., 2019)

8.5. Challenges and limitations

QD-based nanosensors have demonstrated strong analytical performance under laboratory conditions; however, their application to food analysis remains challenging because food matrices contain proteins, lipids, carbohydrates, pigments, salts, vitamins, and naturally fluorescent compounds. These components can have nonspecific adsorption, compete with the analytes for binding, quench the fluorescence emission and/or foul the electrodes or interfere with the electrochemical response, thereby decreasing the analytical accuracy and selectivity. Therefore, one of the key problems in the use of pesticide sensors based on QDs is the reduction of the matrix interference (Dhaffouli, 2026; Qureshi et al., 2023). Therefore, proper sample preparation is crucial for the successful and accurate analysis of pesticides in food products. Common sample-preparation procedures include filtration, centrifugation, dilution, solvent extraction, solid-phase extraction (SPE), QuEChERS, and magnetic solid-phase extraction, depending on the sample type. All these methods will effectively minimize matrix interference but they are also time consuming, complicated and costly to operate. As a result, numerous recent sensing platforms have been developed based on the QuEChERS and magnetic extraction combined with fluorescence or electrochemical detection for the determination of pesticides in apples, tomatoes, cucumbers, tea, rice, and drinking water, which led to a gain in the analytical accuracy of the complex matrix (Gaviria-Arroyave et al., Oct 16 2023; Sinha and Ray, Dec 24 2024; Xiong et al., Apr 7 2022).

New developments of surface engineering, antifouling coatings, molecularly imprinted polymers (MIPs), aptamer-based recognition and magnetic nanocomposite-assisted separation have made significant improvement in the selectivity of the sensors in complex food matrices. For instance, pesticide detection in fruit and vegetable extracts with MIP-functionalized QD sensors and aptamer-QD nanoplatforms in tea, milk and environmental water has been shown to have excellent selectivity for organophosphorus pesticides. Similarly, magnetic QD nanocomposites have led to the rapid separation and enrichment for fluorescence analysis improving recovery and reducing matrix interference (Feng et al., 2025; Mirres et al., 2022; Pushparajah et al., 2025; Xiong et al., Apr 7 2022). Another crucial condition for the practical implementation is the validation using the authentic food samples. In recent studies, quantum dot nanosensors have been investigated for the purpose of detecting different types of genuine as well as spiked food and environmental samples like apples, oranges, tomatoes, cucumbers, spinach, tea, honey, milk, rice, and drinking water. In cases of availability, the results obtained were matched with well-established chromatographic methods such as HPLC, GC-MS/MS, and LC-MS/MS. The recovery range was found to be between 85 % to 115 %, and relative standard deviation was found to be less than 8 % in most of the cases (Feng et al., 2025; Gaviria-Arroyave et al., Oct 16 2023; Pushparajah et al., 2025; Sinha and Ray, Dec 24 2024; Xiong et al., Apr 7 2022). However, larger inter-laboratory validation, which will involve testing of more authentic samples, is required in order to define the capabilities of quantum dot nanosensors for practical usage.

So, the future development should consider the integration of highly selective QD nanomaterials, with portable sensing devices, with data analysis, through a smartphone, with microfluidic systems and with automated sample preparation technologies that can provide rapid, extraction-free and on-site pesticide analysis in complex food matrices. The transition of QD based nanosensors from proof-of-concept lab demonstrations to common practice of food quality control and environmental monitoring will be greatly hastened by such developments (Kumar et al., 2025; Savas and Gharibzahedi, Sep 2 2025). Table 14 summarizes matrix-specific sample pretreatment, major interferences, analytical performance, validation methods, and practical challenges associated with QD-based pesticide detection. While numerous pesticide nanosensors have shown impressive analytical capabilities based on QD, very few have reached the commercial product stage. The major issues highlighted by the researchers between the lab and the market are related to the difficulties of scaling up synthesis, batch-to-batch reproducibility, storage stability, manufacturing costs, and quality control (Rafi et al., Feb 2025; Zou et al., 2024). In addition, the analytic performance and the matrix effect of most reported sensors have been evaluated in limited and/or laboratory-prepared or spiked samples, leaving the robustness and the matrix effect of these sensors in real food matrices in routine use unknown (Veiga-del-Baño et al., 2024). Another concern is regulatory approval, which is a big hurdle, especially for heavy metal-based QDs, as extensive toxicological studies, environmental risk assessments, standardized protocols for validation, and life-cycle assessment are necessary before commercialization (European Food Safety Authority (EFSA), 2024; Organization for Economic Co-operation and Development (OECD), 2024) (Bleeker et al., Mar 2023; More et al., Aug 2021). Therefore, in addition to enhancing the analytical sensitivity of these QDs, the development of environmentally friendly QDs, scale-up technologies, industrial and regulatory standards for quality control, and user-friendly portable sensing devices connected to digital technologies will be essential for commercialization in the future (Jin et al., 2025; Kareem et al., 2026; Savas and Gharibzahedi, Sep 2 2025).

Although QD-based nanosensors offer significant analytical benefits, there are a number of drawbacks that currently limit their use to laboratory demonstrations and prevent them from being used routinely for pesticide monitoring. Major problems are matrix dependent signal interference, sample preparation, lack of selectivity when nonspecific recognition methods are employed, surfaces and recognition elements of QD instability, batch-to-batch variability and inadequate validation with authentic samples. Heavy-metal containing QDs have other challenges that must be addressed for their use in food and environmental applications, such as toxicological and environmental issues of possible release of metal ions. In addition, the use of multiple components in hybrid QD architectures can enhance analytical performance, but may complicate fabrication, production, and large-scale manufacturing and quality control. While many sensors are reported to be evaluated using buffered or spiked samples under controlled laboratory conditions, method standardization and regulatory acceptance, long-term stability and inter-laboratory reproducibility are comparatively underdeveloped. It is therefore important to not only consider the lowest reported LOD, but also the sensitivity of the nanosensors along with their selectivity,

Table 14
Matrix-specific practical applications of QD-based pesticide nanosensors, including representative samples, sample pretreatment, dominant matrix interferences, analytical performance, validation methods, and major practical challenges.

Application Category	Representative Samples	Typical Sample Pretreatment	Dominant Matrix Interference	Analytical Performance	Typical Validation Method	Major Practical Challenges	Ref.
Aqueous environmental samples	Drinking water, river water, groundwater, wastewater	Filtration, membrane filtration, pH adjustment	Dissolved organic matter, metal ions, suspended particles, humic substances	Highest sensitivity; recoveries typically 95–105%; lowest LODs due to relatively simple matrices	LC–MS/MS, HPLC, standard water analysis methods	Natural organic matter may cause fluorescence quenching or electrochemical interference	(Addink and Hall, 2021; Zawadzki, 2023)
Minimally processed agricultural samples	Apples, tomatoes, cucumbers, lettuce, spinach, peppers	QuEChERS, solvent extraction, filtration, centrifugation	Pigments (chlorophyll, carotenoids), sugars, organic acids, plant metabolites	Recoveries generally 85–110% with satisfactory precision after extraction	LC–MS/MS, GC–MS/MS, HPLC	Matrix-induced fluorescence quenching and nonspecific adsorption require efficient cleanup	(Anastassiades et al., 2003; Chen et al., Mar 20 2025; Lehotay et al., 2005; Liu et al., 2019; Yu et al., Dec 6 2022)
Complex food matrices	Milk, tea, honey, edible oils, fruit juices, cereals, rice, processed foods	Protein precipitation, QuEChERS, SPE, magnetic SPE, dilution	Proteins, lipids, fats, polyphenols, carbohydrates, emulsifiers, natural fluorophores	Recoveries generally 85–115% with RSD usually <8% following optimized pretreatment	LC–MS/MS, UPLC–MS/MS, GC–MS/MS	Severe matrix effects, electrode fouling, optical interference, extensive sample preparation, limited validation in real samples	(Huertas-Pérez et al., 2024; Liu et al., 2024; Veiga-del-Baño et al., 2024; Yang et al., 2024)

matrix tolerance, accuracy, precision, stability, safety, cost, and compliance to relevant regulatory requirements. Overcoming these challenges is key for translating QD-based nanosensors from laboratory prototypes to practical, reliable, and commercially practical, routine pesticide monitoring devices (Niu et al., 2023; Rani et al., 2024). Unlike the platform-level comparison presented in Table 12, Table 14 focuses specifically on matrix-dependent sample pretreatment, matrix interference, validation, and practical implementation.

8.5.1. Distinct analytical challenges across different sample types

The performance of the nanosensors developed with the QD has been found to be very good in laboratory conditions, but in real applications, the performance observed depends on the complexity of the sample matrix. On an analytical point of view, the detection of pesticides can be classified generally in three different application domains: aquatic environmental samples with different physicochemical characteristics, minimally processed agricultural products and complex food matrices, each of which presents different physicochemical challenges, affecting the sensitivity, selectivity and reproducibility of the sensor. In practical food safety, the aim is not necessarily to reach the lowest detection limit but to gain reliable quantification in the area of regulatory decision levels determined by WHO, EPA, EFSA, and other regulations. Thus, the interpretation of analytical performance can include various parameters, such as the recovery, selectivity, reproducibility, matrix tolerance, and correlation with the existing chromatographic techniques. The efficient extraction of analytes and mass transfer, the stability of the fluorescence and surface interactions at the sensing interface are directly influenced by the composition of the sample matrix. To also understand how QD-based nanosensors would perform in real-world matrices, it is necessary to evaluate these nanosensors in other matrices as well, instead of just using the results from under ideal laboratory conditions. Optimization of the sensors for the specific matrices has thus become increasingly important in the design and validation of the sensors used in food safety monitoring. The typical environmental samples that are used for water analysis are the simplest matrices to work with for pesticide detection, such as drinking water, river water, groundwater, irrigation water and wastewater. The fluorescence or electrochemical signals of the quantum dots are measurable with very low background signals in these samples because they have relatively low concentrations of proteins, lipids and endogenous fluorophores. However, even when the above do not cause fluorescence quenching, suspended solids, humic substances, inorganic salts and metal ions can still cause changes to the electrochemical response or excite light scattering. Consequently, it is often possible to obtain high analytical recovery and low detection limits by simple filtration, pH adjustment or other pretreatment steps. The nanosensors based on QDs have been proven to have outstanding environmental monitoring capabilities, such as excellent linearity, sensitivity, and repeatability, and have been widely used in environmental water samples, especially in periodic environmental monitoring and rapid detection of pesticide contamination in field tests.

Minimally processed agricultural products (MPAPs) like fresh fruits, vegetables, grains, leafy crops and others contain naturally occurring pigments, carbohydrates, vitamins, phenolic compounds, organic acids and secondary plant metabolites, which creates a higher degree of analytical complexity. The influence of these endogenous materials can be a source of significant negative impact on analytical accuracy, such as due to fluorescence resonance energy transfer, inner-filter effects, nonspecific binding or surface passivation with quantum dots. Moreover, higher sensitivity may be achieved by using complex plant extract, but it can contaminate the surfaces of the electrodes, which can lead to a decrease in the stability and repeatability of the sensor. To reduce these matrix effects, various sample preparation methods such as QuEChERS extraction, centrifugation, membrane filtration, dilutions, dispersive solid-phase extraction and adsorbent materials cleanup are used prior to nanosensor analysis. These methods greatly enhance the recovery of the analytes and lower the interference due to co-extracted matrix components. The most difficult matrices are complex foods like milk, edible oils, tea, fruit juices, cereals, honey, seafood, meat products and processed foods. Proteins, lipids, polysaccharides, emulsifiers, polyphenols, vitamins and other macromolecules with effects on the fluorescence emission can be present in high concentration within these matrices, which can bind to recognition sites, may cause nonspecific adsorption, or cause fouling of the electrode surface. Thus, the performance of the sensor in simple aqueous media cannot be interpreted in the same manner as in such a complex and heterogeneous matrix as these without thorough testing under realistic conditions. To tackle these challenges, current research has focused on developing matrix-specific protocols for sample preparation along with the development of more sophisticated sensing strategies including anti-fouling surface coatings, creation of molecularly imprinted polymers, aptamer-functionalized quantum dots, magnetic nanoparticle-assisted separation, and hybrid nanocomposite interfaces. The engineering solutions significantly enhance selectivity,

analytical reliability and repeatability, and the sensitivity in real food matrices (Mirres et al., 2022; Qiao et al., 2022; Rajeshwari et al., 2026; Zhou et al., 2022).

A key challenge in the implementation and marketability of QD-based nanosensors will be analyzing products in each of the application categories, independently of the others and not assuming results gained from water sample analysis can be directly applied to agricultural products or highly complex food systems. Validation of the analytical method is critical for ensuring analytical reliability and regulatory acceptance, and must include matrix-dependent validation, standardized sample preparation procedures, and complete recovery studies. Therefore, future work should be directed towards the development of universal, matrix adaptable sensing platforms that, while maintaining high sensitivity, selectivity and operational stability in various food and environmental matrices, will also be able to operate in these different matrices. Such a classification will give a more realistic idea of the robustness of the sensors while rationally designing next-generation nanosensors based on quantum dots for use in routine pesticide monitoring in real-life applications.

8.6. Historical development of QD-based nanosensors for pesticide detection

A transition from relatively simple optical-type nanosensors to multifunctional, hybrid, and integrated nanosensors for pesticide detection has taken place. The first generation of QD sensor technology was based on the unique size-dependent optical and electronic properties of semiconductor QDs, especially their strong and tunable fluorescence. The first strategies involved targeting the analyte through a quenching or enhancement of fluorescence caused by interactions between the target analyte and the surface of the QD. While these systems were successful in showing the potential of the use of QDs in sensitive pesticide analysis, they suffered from a lack of molecular selectivity, matrix interference and concern over the use of heavy-metal based QDs (Zhou et al., 2018).

Following stage of development was surface functionalization of QDs with specific recognition elements such as enzyme, antibody, aptamers and molecularly imprinted polymers (MIPs). This evolution turned QDs from a class of materials that primarily generated signals to a class of compounds that also function in molecular recognition and signal transduction to become multifunctional sensing devices. The systems based on acetylcholinesterase (AChE) gained special importance for the screening of organophosphate and carbamate pesticides, while aptamer-, antibody- and MIP-functionalized QDs opened up avenues for more selective recognition of individual targets for the pesticides (Niu et al., 2023; Zhou et al., 2018).

The field then shifted to hybrid QD designs by incorporating graphene-like materials, metal–organic framework (MOF), magnetic nanoparticles, metal nanoparticles, conductive polymers, and other functional materials. The objective of these hybrid systems was to address certain drawbacks of single QDs, such as enhancing electron transfer, charge separation, analyte enrichment, catalytic activity, signal amplification or matrix tolerance. Concurrently, the types of sensing mechanisms went beyond the traditional fluorescence to electrochemical, photoelectrochemical (PEC), electrochemiluminescence, surface-enhanced Raman scattering (SERS), and multimodal sensing mechanisms (Niu et al., 2023; Sahoo et al., 2017).

However, with the demand for safer and more environmentally friendly sensing materials, more recent development has focussed on the carbon-based quantum dots such as carbon quantum dots (CQDs) and graphene quantum dots (GQDs). The field has also advanced to mobile systems based on smart devices, lab-on-chip and microfluidic systems, and AI and machine learning techniques for signal interpretation and optimization of sensors and multiplex analysis (Niu et al., 2023; Rani et al., 2024). Overall, the evolution of QD-based pesticide nanosensors can be considered a step from material-based fluorescent detection to recognition system-based nanosensors, multifunctional hybrid nanocomposites, and more and more application-oriented and integrated sensors. The transition and the present importance of sustainability, standardization, digital integration and real-world deployment (Section 8) are based on this evolution.

9. Emerging trends and future perspectives

The advancement of QD-based nanosensors for pesticides detection relies heavily on removal of material, analytical, manufacturing, and regulatory obstacles separating laboratory results from everyday application in field and food safety. Although artificial intelligence (AI), portable detectors, microfluidics, and digital technologies have provided huge opportunities for further improvement of integration and use of sensor, the practical effectiveness of the gadgets will depend on their capabilities to be reproduced, stably work, and remain safe and matrix-tolerant. Among the most important tasks for experts in this field is to provide control over QDs synthesis with narrow size distribution, resistance to photodegradation and loss of signal in complex environments, minimum heavy metal discharge, invention of environmentally friendly analogues of Cd-based QDs, increase of surface-coated QDs stability. Recent developments in quantum dot (QD)-based nanosensors indicate a growing shift toward intelligent, integrated, and sustainable sensing platforms. Among the most influential directions is the increasing use of artificial intelligence (AI)-assisted nanosensor design, which can improve sensitivity and selectivity through data-driven optimization. Biosensor engineering using machine learning has been shown to optimize detection toward regulatory limits (for example, ~5.7 ppb for lead) and to enhance selectivity against interfering species. Correspondingly, AI-based sensing arrays incorporating QDs can categorize and detect analytes with high accuracy (>92%), enabling real-time monitoring of food products; they can also be deployed remotely via the Internet of Things (IoT) and smart monitoring systems. Another emerging direction is the development of microfluidic and lab-on-chip platforms that enable sample-in-result-out operation and high-throughput analysis, with automated processing and visualization of multiple sample types simultaneously, incorporating QDs and MXene platforms for edge-computing-based food and environmental safety systems (Yang et al., 2026). Microfluidic biosensors are also being applied to on-site testing using biodegradable and green nanomaterials, including biomass-derived carbon quantum dots synthesized from plant or waste materials. The exceptional fluorescence, low toxicity, and environmental compatibility of these materials support their use in food safety applications and smart food packaging systems, while integrated nanosensor platforms facilitate real-time environmental monitoring and instantaneous data processing (Rastegarpour et al., 2025). For instance, microbial fuel cell-based sensors can detect contaminants and generate energy concurrently, and detection limits of 200 μg/L in actual wastewater have been reported (Kumar and Jujjavarapu, 2025). Even with these tremendous advances, several basic scientific and technological questions have yet to be answered. First, a clearer understanding of the relationships among QD composition, size, surface chemistry, defect engineering, and sensing performance is required for the rational design of next-generation nanosensors (Patra and Shand, 2026). Second, reliability of operation in complex food matrices is still difficult due to the fact that matrix interference, nonspecific adsorption, fluorescence quenching and electrode fouling can greatly affect the analytical accuracy. Third, there are still many obstacles to scaling up manufacturing, batch-to-batch reproducibility, long-term storage stability, and standardized validation protocols that are hindering commercialization. The development of protocol harmonization, regulatory guidelines for QD based sensing materials and extensive life cycle and environmental risk assessment should also be addressed in future research. Interdisciplinary collaboration between materials scientists, analytical chemists, food scientists, toxicologists, environmental engineers, computer scientists and regulatory agencies will be required to address these challenges

(Yuan et al., 2023). These joint efforts will help fast-track toward the creation of smart, sustainable, and market-ready sensing platforms for real-world food and environmental monitoring based on QDs.

9.1. *Knowledge gaps and conceptual framework for QD-based pesticide sensing*

Despite significant advances in QD-based pesticide sensing, several scientific and technical challenges remain unresolved. First, there is no standard analytical approach adopted by studies on sensor performance, which makes it difficult to compare the results across different studies. Differences in experimental conditions, sample-preparation procedures, and validation methods contribute to inconsistent performance assessment. Second, while many of these nanosensors based on QDs show excellent sensitivity in laboratory settings, there are relatively few studies that look at the operational, storage, reproducibility, and batch-to-batch stability. These factors are important for practical deployment, but are not sufficiently explored. Third, most of the reported sensing platforms have been tested for artificially spiked samples instead of natural samples. The presence of co-existing compounds like protein, fats, pigments, natural organic matter and many others, which cause matrix interferences, remains a significant limitation of the reliable analysis in the real world. Environmental safety and sustainability of QD materials is also deemed as one of the knowledge gaps. The former is usually made from heavy metals and have good optical properties, but pose potential toxicity and environmental persistence risks, while the latter are derived from carbon and graphene and have better biocompatibility but tend to be less sensitive to analysis. In the future, it is

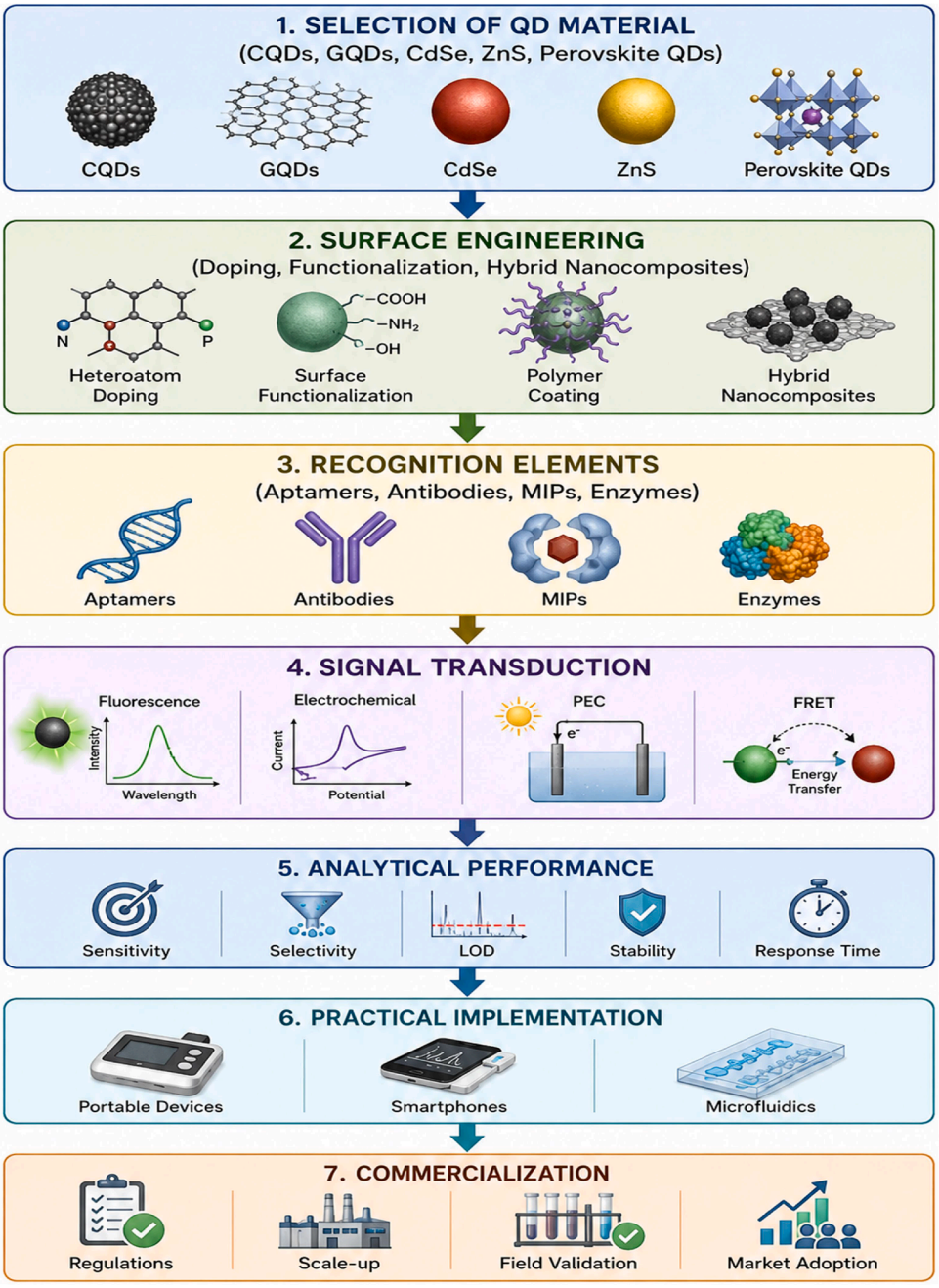


Fig. 11. Proposed design and translational pathway for QD-based pesticide nanosensors, from QD material selection and surface engineering to recognition, signal transduction, analytical performance, practical implementation, and commercialization.

therefore desirable to develop environmentally friendly QDs with high sensing performance. Scalable production, device integration, miniaturization, quality assurance standardization and cost-efficient fabrication are areas of little engineering investigation. Moreover, the regulatory acceptance, validation based on international standards and commercialization paths have been given less attention than the development of the sensors at the lab-scale. A multi-disciplinary team of materials scientists, analytical chemists, engineers, toxicologists and regulatory agencies will need to work together to address these knowledge gaps. Moving forward, standardized validation protocols, environmentally-friendly QD materials, hybrid nano composite engineering, AI data analysis, portable sensing systems, and integrated microfluidic platforms are all important areas of interest that should be explored to expedite the translation of QD-based nanosensors from the lab to food safety and environmental monitoring (Hassan et al., 2025; Inês and Cosme, 2025; Zhao, 2025). Fig. 11 illustrates the proposed design and translational pathway for QD-based pesticide nanosensors, linking material selection and surface engineering with recognition, signal transduction, analytical performance, practical implementation, and commercialization.

10. Conclusions

Nanosensors based on quantum dots (QDs) have been high in the list of potential sensing platform options for pesticide-residue monitoring due to their tunable optical and electronic properties, high surface-to-volume ratios, and surface chemistry that facilitates their integration with imaging, electrochemical, photoelectrochemical and Förster resonance energy transfer (FRET)-based sensing strategies. This review shows that the analytical performance is determined not only by composition of the QDs, but also by the synergistic effect of the analytical properties of the QD, its surface functionalization, recognition elements, signal-transduction mechanisms, hybrid nanocomposite architecture, and device configuration. Thus, the rational design of the sensing interface is more critical than the choice of a QD that has an intrinsic high analytical response. Even though there has been significant progress, the translation of QD-based nanosensors from the lab to regular pesticide monitoring has been limited. The issues that are significant are matrix interference in complex food samples, long-term stability, batch-to-batch reproducibility, analytical validation of the procedure, lack of a standard protocol, scalability, cost and regulatory acceptance. Heavy metal containing QDs will need special consideration as the risk of release of the metal ions may limit their use in food and environmental systems, as well as their persistence in the environment. Future studies should focus on the increasing use of QDs that are free of heavy metals and environmentally friendly, understanding the green synthesis process, life cycle and environmental risk assessment, and surface engineering methodology that does not negatively affect analytical results. Future developments should not simply be aimed at reporting lower limits of detection but at capturing and quantifying data of increasingly high value. The importance of reliable quantification at regulatory relevant concentrations, matrix tolerance, accuracy, precision, operational stability, inter-laboratory reproducibility, and direct comparison with existing chromatographic reference methods should be highlighted, using authentic materials. For meaningful comparisons between different platforms, standardized protocols for material characterization, sensor fabrication, sensor validation, and sensor performance reporting will be critical. Portable devices incorporating QD nanosensors, microfluidics and smartphone-enabled readout along with artificial intelligence could further facilitate rapid and decentralized pesticide screening. All of this technology must be developed in parallel with enhancing the safety of the material, analytical robustness, manufacturing quality, and regulatory compliance. Finally, interdisciplinary collaborations between materials scientists, analytical chemists, food scientists, engineers, data scientists, toxicologists and regulators will be essential for successful commercialization. The next steps toward the future of pesticide sensing using quantum dots will not only be increased sensitivity but the ability to create safe, reproducible sensing systems that can withstand a matrix, are standardized, and are commercialized for true real world sensing.

Ethical statement

Studies in humans and animals:NA.

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Farhang Hameed Awlqadr: Writing – original draft. **Mohammed N. Saeed:** Writing – original draft, Visualization. **Ammar B. Altemimi:** Formal analysis. **Muhammad Waqar:** Formal analysis. **Ahmad F. Hama Sdiq:** Writing – original draft, Formal analysis. **Tablo H. Salih:** Writing – original draft. **Muhammad Yasir:** Writing – review & editing. **Anubhav Pratap-Singh:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.afres.2026.102626.

Data availability

No data was used for the research described in the article.

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